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NOURISHMENT OF THE GREENLAND CONTINENTAL GLACIER

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ABSTRACT

Nourishment of the Greenland continental glacier has been claimed by some glacialists to be by cyclones which cross it and deposit snow upon it. This claim appears to be on the basis of synoptic weather charts made from a few widely spaced stations established within fjord mouths at which observations of wind force and direction have little value. In but two observational years, 1930–31 and 1932–33, have a sufficient number of good meteorological stations been set up, with one or more in the interior. It has thus been possible to make out the tracks of the cyclones that arrive at the Greenland coast. Co-ordination of these observations has shown that these cyclones are halted at the west coast and pass up Davis Strait. During the summer they invade the glacier in southern Greenland by at most a hundred miles, and in the summer only. They bring rain, not snow, and so they cause liquidation, not nourishment. Nourishment reaches the glacier almost wholly within a cold interior region, the heart of the glacial anticyclone; and this snow is largely swept out to the glacier margins during the long winter, where it is melted in the early summer months together with some of the underlying ice. Today, in a receding hemicycle of glaciation, the Greenland glacier is notably undernourished and is actually shrinking in size.

INTRODUCTION

In three extensive papers which have very recently appeared, it has been asserted that the nourishment of the Greenland continental glacier is, and has been, by cyclones which have approached from the west and have given up their moisture in the form of snow while making the transit of the island. The authors of these articles are well-known students of glaciation, and one of them, Dr. Max Demorest, has had very considerable experience as a meteorologist in Greenland.[1]

Of the others, Mr. Francois E. Matthes of the United States Geological Survey, has been a student of mountain glaciers, and he states in an extended monograph on *Glaciers:* "It is thus manifest that the ice sheet of Greenland is nourished, not by the glacial anticyclone, as Hobbs supposed, but in spite of it, by ordinary cyclonic storms."[2]

Richard Foster Flint,[3] whose studies have had to do largely with Pleistocene glaciers, asserts: "Cyclones cross the Greenland ice sheet now and precipitate snow upon it."[4]

[1] Dr. Demorest has served as an aerologist in two of the University of Michigan Greenland expeditions, and he has since carried out with much success studies of glacier ice. His lamented death in Greenland was an irreparable loss to glaciology.

[2] *Glaciers, Physics of the Earth*, IX (New York: McGraw-Hill Book Co., 1942), p. 187.

[3] "Growth of North American Ice Sheet during the Wisconsin Age," *Bull. Geol. Soc. Amer.*, Vol. LIV (1943), p. 344.

[4] Though Flint cites many authorities in reference to the nourishment of a continental glacier, he may be unaware of several studies on the glacial anticyclone, since he nowhere refers to them or cites them in his three-page bibliography.

In his paper Demorest asserts: "Those who adhere to the belief that ice-sheet nourishment is derived solely from anticyclonic circulation will reject this explanation .... for they hold that cyclonic disturbances do not migrate more than a few miles across the margins of an ice sheet..... "[5]

The above-cited assertions are impressive for their tone of finality and would seem to leave little opening for argument. I propose, however, to consider what evidence there is (1) that cyclones cross Greenland and (2) that there has been nourishment of the glacier by the glacial anticyclone.

EVIDENCE ON THE TRACKS OF LOW-PRESSURE AREAS NEAR GREENLAND

During the first international polar year (1882–83), three meteorological stations were located in southwestern and southern Greenland (at Godthaab, in southwestern Greenland, and at Ivigtut and Julianehaab, less than 100 kilometers apart, in extreme southern Greenland). The synoptic charts which were based upon the widely spaced polar network of stations showed cyclones crossing Greenland as though it were an expanse of sea. Supposed storm tracks across the inland ice were discussed by Edouard Vincent.[6]

In more recent times the Meteorological Institute of Denmark has maintained a number of second- and third-grade meteorological stations, all located within fjord mouths on the west, south, and southeast coasts of Greenland. The usual ground-weather data from these stations have been sent out daily by radio and have been entered in the daily synoptic weather charts which have been issued by the Deutsche Seewarte at Hamburg. As in the case of the data supplied by the three Greenland stations during the first international polar year, and wholly without regard to what has since been learned from sledging expeditions over Greenland, these daily weather observations have been entered on the charts *on the pure assumption that cyclones traverse the high dome of ice as though it were an expanse of sea. The very widely scattered wind observations have been grouped to show isobars consistent with the fundamental assumption.*

Until the year 1930–31 no single station had been maintained in the interior region of Greenland. Greenland has a length of about 1,400 miles, a breadth of about 600 miles, and attains to elevations in excess of 10,000 feet. Generally reliable, as far as barometric readings are concerned, the observations for wind direction and force at the coastal stations are not only unreliable but often false. This is for the following reasons: located as they are within fjords, where the wind always follows the local fjord course either in one direction or the other, the official observations of wind direction sometimes vary from the true value by as much as 40° of arc. The movement of the air within the fjord is comparable to that of water flowing within elbow pipes. Wind force, also, if observed near the base of the fjord, may have little relation to that above. To illustrate, I will cite that wise, veteran administrator of Greenland, Dr. Henryk Rink, who wrote of an approaching storm seen from within a fjord:

> Then suddenly the storm breaks, but first of all one sees the snow whirling over the highland, and if one is on the ice of the fjord under the

[5] "Ice Sheets," *Bull. Geol. Soc. Amer.*, Vol. LIV (1943), p. 381.

[6] "Sur la marche des minimas barométiques dans la région polaire arctique du mois de septembre, 1882, au mois d'août, 1883," *Mém. Acad. Roy. des Sciences, des Lettres et des Beaux-artes de Belgique*, 9 pls. *classe des sciences*, Vol. III (2d sér., 1912), pp. 1–20.

great steep cliffs to the north of Umanak, one hears the storm whistling and roaring, while below on the ice there is perfect calm; up there it blows two or three days or longer. . . . .[7]

Further, to indicate the false nature of the Hamburg synoptic charts where based on the Greenland official meteorological observations, I may refer to an experience while sailing in a motor schooner down the Greenland west coast in the summer of 1927. We were en route to our base at the head of the Söndre Strömfjord when we were caught in a fierce storm and had to take refuge at Olsen's Harbor behind the island of Inugsugtussok. There we were soon joined by the halibut fleet, to be storm-bound for more than a week. It was important that we should reach our base as early as possible, and against sound advice I set out again on the third day, only to be forced back after a half-hour outside. In all, we were held storm-bound for eight days by a summer storm which the veteran Fiskemeester Jensen declared to be the worst in his experience of eighteen years with the halibut fleet. Back in civilization I was interested to look up the synoptic weather charts only to find that the isobars indicated a relatively flat surface for the period, very likely because observations in the coastal stations had given no indication of the force of the wind or of a fall in pressure.

It is presumed that the claims of Matthes, Flint, and Demorest for the transit of cyclones over Greenland are based on these charts, with such support as is given by the known approach of cyclones along the track of storms to southwestern Greenland and the movement of cyclones along the Greenland east coast.

Though no weather station had been set up on the Greenland glacier (save close to its borders) until the observing year 1930–31, very important facts had been learned from observations made during sledging trips and particularly during transections of the glacier. These meteorological observations en route were in entire agreement in showing that the winds above the ice are throughout katabatic with no important temporary deviations, such as must inevitably have occurred during the passage of cyclones. Such sledging observations were, of course, not synchronized, and all were taken during the months of summer and early autumn. Observed during a wide range of years (1878–1936), they nonetheless conform to a common model of wind directions, all with exception of some within a central area (see Fig. 1) directed downslope toward the margins.

Transections of the Greenland glacier by exploring expeditions, when carried out by dog sled, have occupied from four to ten weeks, so that a number of cyclones must approach Greenland from the southwest along the usual track of storms during these periods.

During such a storm it is imperative that the sledge party go into camp and into sleeping sacks day and night for the duration of the storm. Thus, while the storm is on, often for a week or longer, *the camp becomes a fixed meteorological station* in the interior of Greenland, a fact of great importance, but one little appreciated by the glacialists. Because of this stationary position of the camp, or of the party, it is thus possible to register throughout the period of storm all the usual meteorological data, and especially those of air pressure and of wind force and direction. There is entire agreement in the records, which show that barometric recordings are steady throughout—they do not indicate the usual drop followed by rise, such as occur

[7] *Grönland* (German ed.; Stuttgart, 1860), p. 111.

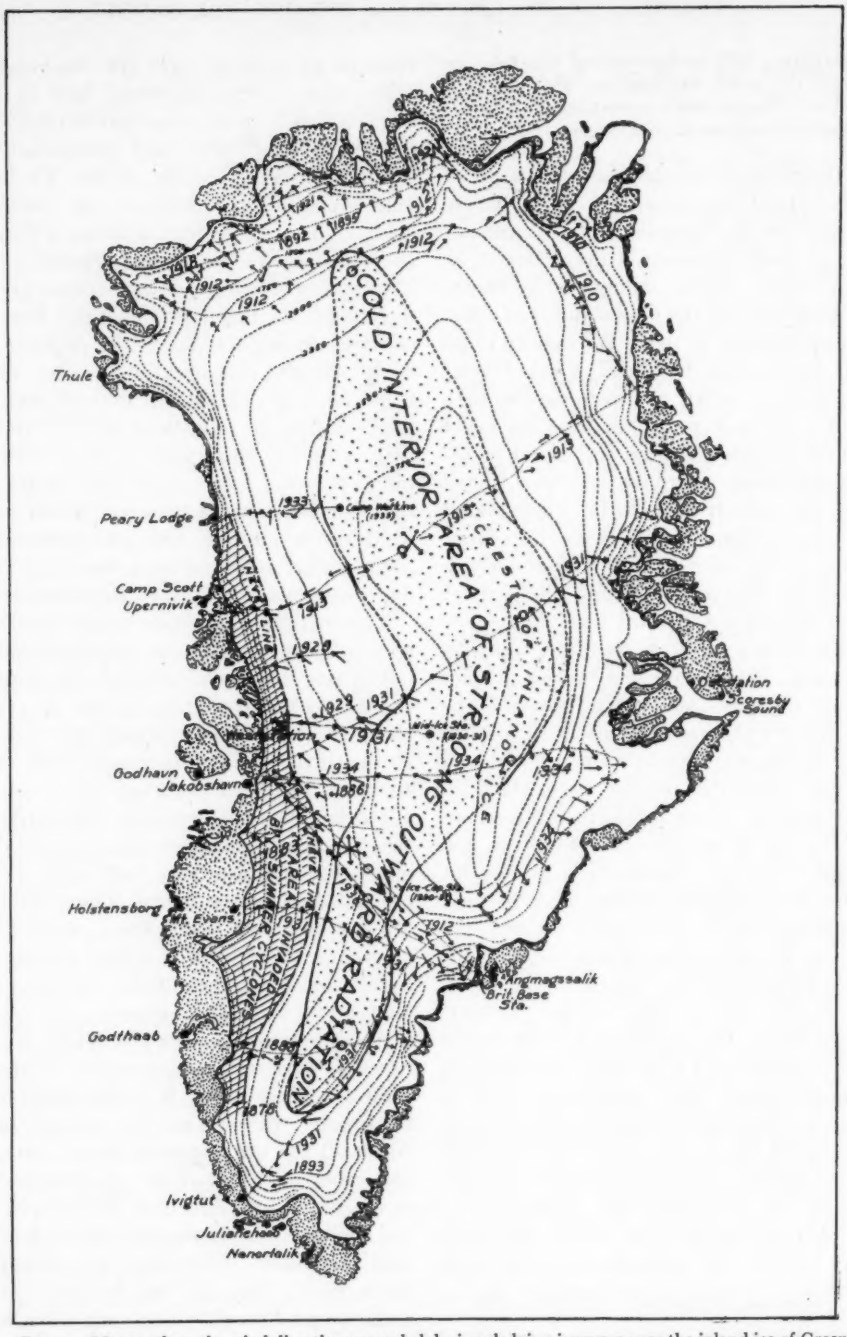

FIG. 1.—Map to show the wind directions recorded during sledging journeys over the inland ice of Greenland. The central area where meteorological conditions are different in some particulars is indicated on the map.

during passage of a cyclone—and the wind direction varies by a few degrees only—it is throughout downslope and does not pass through the cycle of changes characteristic of transit of a cyclone. One dominating characteristic of the storm is the terrific velocity of the wind, sometimes over 100 miles per hour, and its roaring is such that shouts do not carry between tents, even if only 25 feet apart.

CRUCIAL TESTS CONCERNING THE TRACKS OF GREENLAND CYCLONES MADE IN THE YEARS 1930–31 AND 1932–33

In the year 1930–31 for the first time in history meteorological stations were set up over the inland ice, and coastal stations were established provided with equipment for daily aerological observations (see Fig. 2). In addition to the German station at Mid-Ice, maintained for the entire period near latitude 71°, there were three other stations, all located near the coast, but one of them on the inland ice. In addition, a British station was established for seven winter months near the crest of the inland ice in latitude 66.5° (not complete as regards data), and a base station operated for the entire year on the east coast in nearly the same latitude. The University of Michigan maintained two aerological stations, one near Upernivik on the west coast near latitude 72.5° N., and the other in extreme southern Greenland near latitude 61° N.

This group of stations was in operation during 1930 and 1931. This offered the first opportunity really to test the question of whether cyclones make the transit over Greenland, though a clear decision had been foreshadowed by our Mount Evans observations made a year earlier.[8]

[8] See L. R. Schneider, "Greenland West-coast Foehns, etc.," *Monthly Weather Review*, April, 1930, pp. 135–40.

As director of the two University of Michigan stations, I offered to Dr. Johannes Georgi, director of the German Eismitte station, and the most expert and experienced meteorologist in that expedition, the use of copies of all our observa-

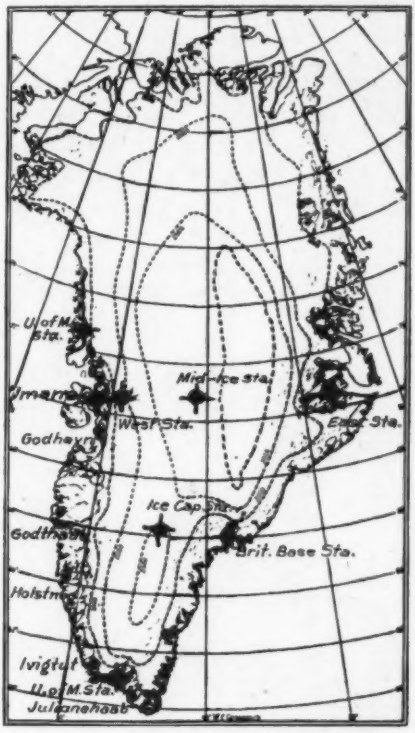

FIG. 2.—Map of Greenland to show the distribution of special meteorological stations during 1930–31. Four German stations were established in an east-west line near latitude 71° N., two on the inland ice, three of them supplied with equipment for daily upper-air studies. Two University of Michigan stations similarly equipped were set up on the coast and maintained for most of the same period; one in the extreme south of Greenland (latitude 61° N.), and the other on the west coast near latitude 72½° N. Two stations of the British Air Route Expedition, but without aerological equipment, were maintained, one on the east coast in latitude 66° N. for the entire period, and the other on the crest of the inland ice in nearly the same latitude, but for seven winter months. All were in operation for the months of January and February, 1931.

tions in advance of their publication. This was so that he might prepare synoptic charts with the use of all stations in operation. This task he accepted, and he secured the British data as well. His published charts were for late January and most of February, a period covered by all the stations, and with the results shown in Figures 3 and 4.

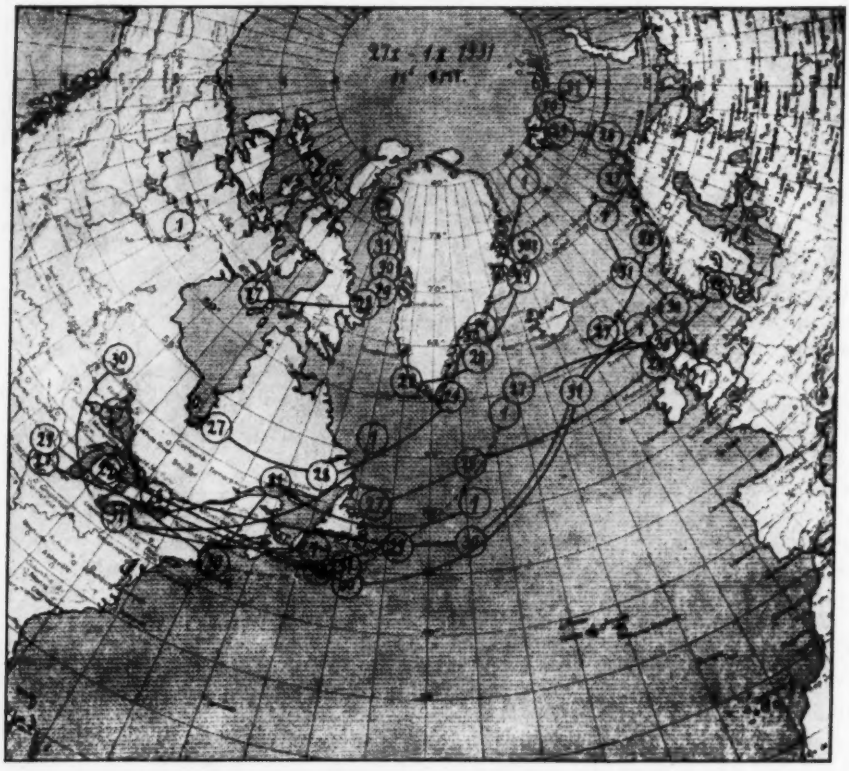

FIG. 3.—Tracks of depressions, January 27–February 1, 1931. (After Georgi)

Georgi's conclusions from this study are as follows:

> With the disposable material, i.e., the paper of Mr. Mirrlees, observations placed at my disposal by Mr. W. H. Hobbs, and by the Danish Meteorological Institute, I have compiled the weather maps of the Deutsche Seewarte for the two weather periods mentioned above. One will see in the two figures the tracks of depressions. The centre of every low is signified by the date. It is seen that the tracks have apparently been modified by the existence of the Greenland continent. It is evident that the western slope is mostly influenced by the few, but stationary lows of the Davis Strait, whose normal eastward movement is stopped there. On the other side the region near the English station is influenced to a higher degree by the lows between Southeast Greenland and Iceland, and these lows cause the northern storms mentioned above in their rear. But on account of the direction of the east coast the track of these depressions is deflected to the North-east, so that at latitude 71° N., in the middle part of the inland ice, they are no more perceptible.[9]

[9] "Greenland as a Switch for Cyclones," *Geog. Jour.*, Vol. XXXI (1933), p. 344.

In the final reports on the expedition (Vol. IV, Part II, p. 314) the director, Dr. Kurt Wegener, states, "The possibility of a cyclone crossing the inland ice is greater in the summer. In spite of this we could not confirm any clear case in which a cyclone had crossed."

ice for a seven-week period beginning July 3 and ending August 19, 1933. For the full year, August 1, 1932—July 31, 1933, daily aerological observations were carried out at the base station of Peary Lodge on the Greenland west coast (lat. 74° 19′ N., long. 56° 13′ W.), or else at

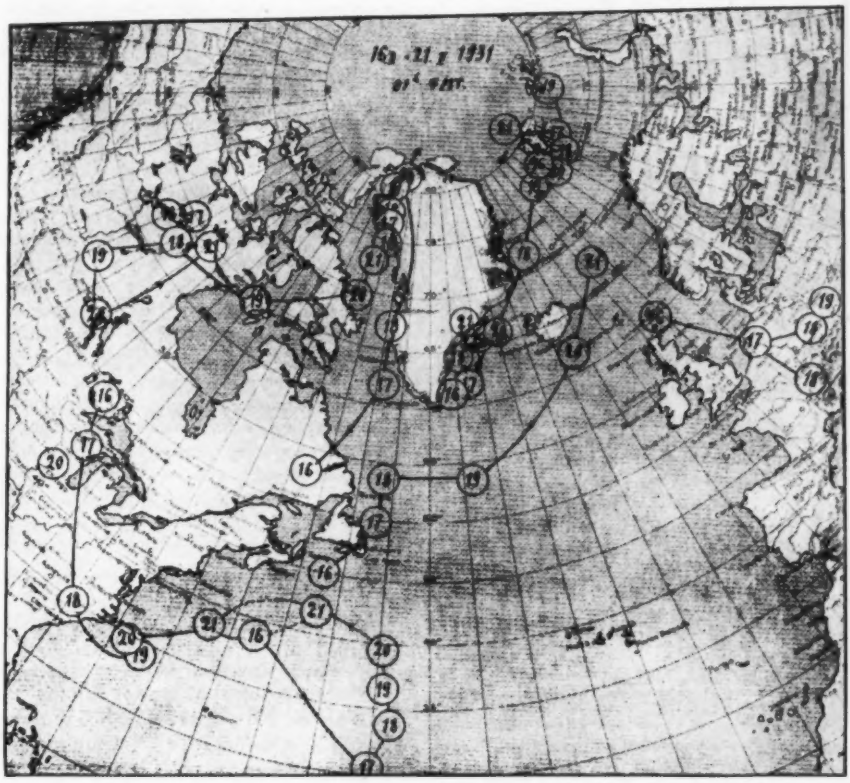

FIG. 4.—Tracks of depressions, February 16–21, 1931. (After Georgi)

A second opportunity to test the question concerning the tracks of cyclones arose during the second international polar year (1932–33). During that year the University of Michigan–Pan American Airways Expedition, under Dr. Ralph L. Belknap, maintained a camp for ground observations at Camp Watkins (elev. 8,840 ft., lat. 75°) on the inland

the nearby station at Kraulshvan. For the same period similar aerological observations were carried out on the west coast by Danish aerological stations located at Godthavn (lat. 69° N.) and at Thule (lat. 76.5° N.). Other stations of the same character were operated on the east coast by a French expedition located at Angmagssalik (lat. 65.5° N.), and by a

Dutch station located at Scoresby Sound (lat. 70.5° N.). The location of these several stations is set forth in Figure 5.

With this synchronized series of meteorological observations Dr. Belknap prepared synoptic charts (see Fig. 6).[10]

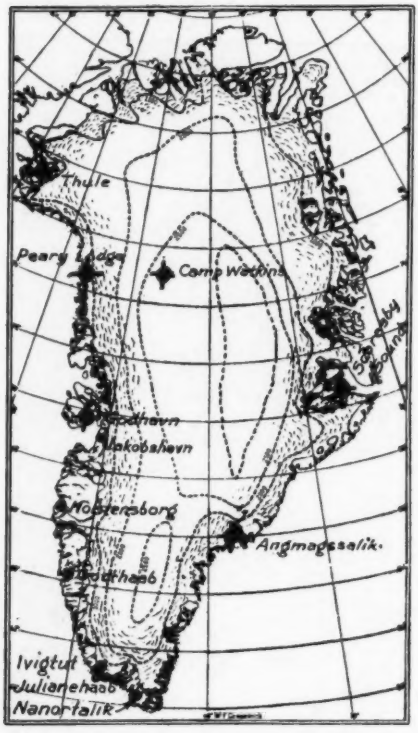

FIG. 5.—Map to show the location of meteorological stations for the polar year 1932–33. All except Camp Watkins were aerological stations. In addition, the small dots show the location of the usual Danish stations.

These data were combined with those supplied by the synoptic charts of the Meteorological Office of the British Air Ministry, and Belknap in his report concluded:

> From those [observations] for the month of February, 1933, the month having the largest number and the most severe of our storms, a chart was prepared [Fig. 6] showing the location of the center of each separate low-pressure area. This one is the method employed by Georgi and the diagram thus prepared using the February data is another proof of his contention that Greenland acts as a "switch for cyclones." The chart shows the location of the centers from day to day, but more important here is the fact that of over thirty cyclones thus located only one *may* have crossed the ice cap and that one in the southernmost part of Greenland. It also indicates that practically all the lows move up along either the west or the east coast; very often there are separate disturbances moving up each coast simultaneously.
>
> An attempt was made to prepare a similar chart for the anticyclone. The result is such a maze of lines along the coast and out on the inland ice as to be quite unintelligible. It does indicate, however, that there is an anticyclone over the inland ice. The series of lows along the coast on both sides of Greenland and the continual outward movement of air currents along the border are, of course, further evidence of its existence. This anticyclonic condition, the "glacial anticyclone" of Hobbs, is the mechanism that really acts as the "switch" described by Georgi.

THE MARGINAL INVASION OF CYCLONES ALONG THE GREENLAND WEST COAST

Belknap's occupation for the seven-week period in 1933 of his Camp Watkins located on the inland ice 200 miles east of his base at Peary Lodge, afforded him an opportunity to test out this question of the amount of invasion of the ice cap by passing cyclones. He was able to determine with some approach to accuracy the distance within which cyclones passing northward along the west coast of Greenland impinged upon the glacier. No less than 735 barometric recordings at Camp Watkins were synchronized with those at the coastal base during the

[10] Ralph L. Belknap, "Meteorological Report of the University of Michigan–Pan American Airways Greenland Expedition, August 1, 1932—July 31, 1933," *Repts. Greenland Expeditions of the University of Michigan, Scientific Series*, Vol. VI, Part II, pp. 194–95 (1941).

months of July and August. In conclusion Belknap states:

> Cyclonic conditions did not appear to be effective beyond the marginal 25 miles of the inland ice. . . . . There was not a sufficient shift in the wind direction to indicate the passing of a cyclone. . . . .
>
> Twice during this month simultaneous decreases in pressure occurred at the two stations. Between July 9 and 15 a gradual decrease of only 10.7 mbs. was noted at Camp Watkins, but during this period there was much precipitation, a relatively high temperature, and the highest wind velocity of the month. This wind, however, was from the southwest and was recorded before the pressure started to increase. . . . . There is little evidence of such a drop in pressure at either Scoresby Sound or Angmagssalik on the east coast. On the west coast the Ivigtut and Jakobshavn records show a 10 mb. decrease and the Thule record one of 20 mbs. during this same period. . . . .
>
> The hourly cloud observations [at Camp Watkins] show almost a reverse condition from those of Peary Lodge. Cirri forms are included in 85% of the observations, whereas only 55% show intermediate forms. One of their most important characteristics was their tendency to remain motionless. Those for which observations indicated appreciable movement were usually sluggish. The only time the clouds did appear to move rapidly was when high-velocity surface winds were blowing and the direction of movement was closely parallel to that of the surface wind. This would seem to indicate that the surface winds are dominant to a considerable altitude and that the cold glacier and the high elevation [8,840 feet] have resulted in the various clouds occurring at elevations closer to the surface than is normally the case. . . . .
>
> On the way to and from Camp Watkins we often encountered light to dense "fogs" of ice spicules. These patches of fog are continually changing in both aerial extent and density. Apparently, they are quite shallow, since the zenith is usually clear. . . . . Clouds of ice spicules were often observed at Camp Watkins, but because of their movement were seen more frequently when we were sledging. They were also more common after the marginal zone had been traversed. Sometimes they are undoubtedly important sources of nourishment for the glacier since, when present, they are constantly being precipitated.[11]

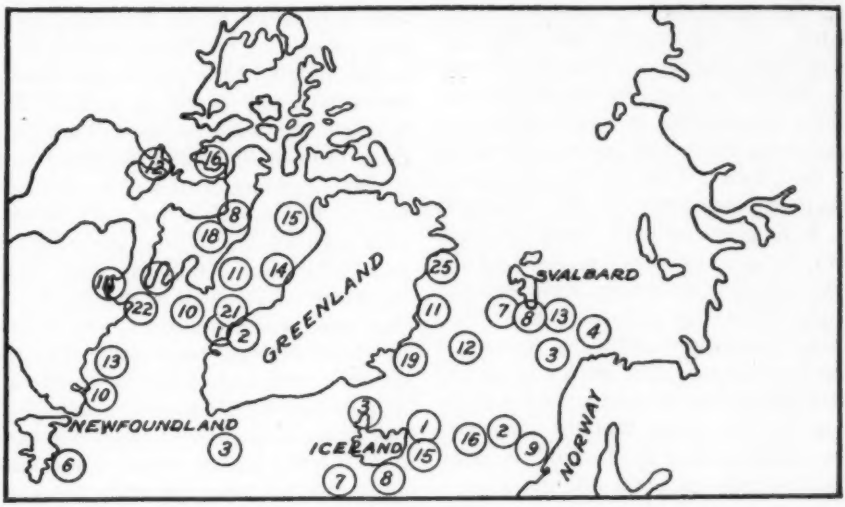

FIG. 6.—Location of centers of "lows" during February, 1933. The numbers indicate the days of the month. (After Belknap.)

There is reason to think that the amount of invasion of the inland ice by the cyclones arriving from the west is

[11] *Ibid.*, pp. 179–81.

considerably greater within the lower latitudes than it is in the more northern ones. Wholly apart from observed meteorological observations made at border stations, we have the evidence from the melting of the winter's accumulation of drift snow, which, at the end of the winter season, is always piled up over and off the margin of the ice surface. By late summer this accumulation has in southern Greenland been completely liquidated, and the explorer who then advances over the glacier must travel on an ice surface of the preceding summer, where his progress is continually being obstructed by surface lakes and streams of melt water. This type of ice surface has been made known by the narratives of A. E. Nordenskjiöld, Peary, Nansen, and, in fact, by every explorer of the region without exception. Ever since the study of Antarctic icebergs by the "Challenger" Expedition of the last century, it has been known that glacier ice is but little affected by even intense solar radiation, for the reason that the sun's rays are reflected; but ice dissolution is almost entirely due to the rain water which falls upon it. It is the rain brought in by the summer cyclones which in southwestern Greenland accomplishes this result, aided by the sand and dust which are blown in at the same time. These latter utilize the insolation to produce sand and dust wells which facilitate the liquidation. Thus summer cyclones which today invade the western glacier margin, instead of nourishing the glacier, increase the ablation and liquidate completely that nourishment in drift snow which had been brought out to the margins during the preceding winter by the cold and heavy katabatic winds of the glacial anticyclone. According to Fritz Löwe,[12] the summer cyclones here melt not only all the winter drift snow which has been left outside the névé line but, at 1,500 feet elevation, some 10 feet thickness of ice each summer. This is in harmony with observations on recession of the glacier front by L. Koch and others.

In winter, on the other hand, the glacial anticyclone controls completely, as is shown by the observations at Weststation.

In latitude 71° N. the Wegener Greenland Expedition had three stations close to the margin of the glacier, which were particularly well located to study the behavior of incoming cyclones. These stations were Weststation (Scheideck) on the glacier at an elevation of nearly 1,000 meters, Kamarujak in the fjord bottom near sea-level directly west, and Umanak in a similar position but some miles to the southwest of Weststation. Holzapfel, in charge of the meteorological observations at these stations, has shown that the summer cyclones on rare occasions are able to push back the cold, heavy air of the surges of the glacial anticyclone and so invade the glacier for short distances. In the winter, however, when the vigor of the anticyclone is greatly intensified, they are quite incapable of doing this. He says of winter conditions:

> Against this cold air [of the surges] cyclones occasionally press and bring bad weather. In Umanak the bad weather is generally connected with winds from the northwest. Here the disturbances press directly into the fjord and push the outflowing air back. At the Weststation, on the other hand, it is only rarely that they can fight successfully against the outflowing cold air; almost always the current of cold air is the stronger. For this reason the disturbances slide over these and bring about a fall of pressure and bad weather at the station without however influencing the wind direction. Its influence is to be seen only in the force of the wind, for the velocity of the outflowing cold air is decreased, and so the wind falls off. Only in the most rare cases does the outward flowing cold air get

[12] *Scot. Geog. Mag.*, Vol. LI (1935), p. 348.

pressed back so far, and apparently influenced from above, that the direction of the surface wind [*Bodenwind*, i.e., in the fjord] is recognizable at the station.

The relationship is not quite so simple in the summer. The cooling off [in cold interior] because of outgoing radiation is then less because in part compensated by the incoming radiation. In consequence the energy of the outflowing air is less and the force of the wind reduced. At such times it frequently occurs that oncoming disturbances push back the cold air. In spite of it even in summer the cold air by far overbalances and entirely similar relations to those of the winter control.[13]

Since the névé line marks the approximate extent of this invasion by the cyclones, it has been drawn in as nearly as is now possible on the map of Figure 1.

EVIDENCE THAT NOURISHMENT OF THE GREENLAND GLACIER IS DERIVED FROM THE INTERIOR AREA

Evidence derived from change in surface level of the Greenland glacier as registered either on stakes set in the surface or from excavations made below the surface is always of a very doubtful nature. This is because (1) the surfaces separating layers cannot be certainly proved to separate annual accretions and (2) large snow accretions or removals, as the case may be, occur at the time of great storms. Thus the time of recording observations, whether before or after a great storm, may be the one crucial factor in the nature of the record made. I may illustrate this by an example, taken from the Antarctic inland ice, where a similar problem is involved.[14]

During Shackleton's advance over the Antarctic inland ice in 1909 from the Beardmore Glacier to a point within 110 statute miles of the South Pole, his party slogged the entire distance of nearly 250 miles through deep surface snow. At the turning-point the party was bivouacked during a terrific three-day blizzard, which was a heavily disguised blessing, for without it the party must have perished on the return. On the back track the ice surface throughout was found swept absolutely clean to a hard undersurface on which only the sledge tracks and footprints stood up in relief. Over this surface record speed was made under sail and with no loss of time from pioneering the trail. These sweepings were later found piled up as a deposit some 60 feet deep over the low portion of the Beardmore Glacier.

The condensed moisture which falls at some moment at any given point on the inland ice surface is the algebraic sum of several quantities, all of which are unknown. They are (1) the locally freshly precipitated snow, (2) the drift snow, (3) the deposited rime, which is often an important factor, and (4) the ablation. Included in the drift snow is eroded snow drilled from the surface by the hard snow particles. The essential equation for change in level is precipitated snow (w), + drift snow (x), + rime (y), + ablation (z), with due regard to the algebraic sign of each factor.

The hard layers sometimes assumed to separate annual accretions are far more likely to represent individual summer rainfalls, such as Belknap found to occur as much as a hundred miles in from the margin of the glacier. It is likely also that a nightly deposit of rime may at times be responsible for the hard layer which holds down the snow.

THE CENTRIFUGAL BROOM

The problem of nourishment of the Greenland glacier is not, however, pri-

[13] R. Holzapfel, *Wiss. Ergeb. der Deutsch. Grönland-Exped. A. Wegener 1929 und 1930–1931*, Vol. IV, Part II, p. 248.

[14] E. H. Shackleton, *The Heart of the Antarctic*, Vol. I (Philadelphia: Lippincott, 1909), chaps. xxiii–xxiv.

marily concerned with the temporary snow accretion over different portions of the ice-cap surface *but only with that which is held down*. The problem is largely reduced, therefore, to two factors, the wind drift and the ablation; and outside the névé line (which in latitude 70 is about 30 miles in from the west coast) wholly to the latter. Neither Flint nor Matthes seems to have brought the wind drift or the ablation into their discussion, though they are the most vital of the factors involved.

I have always treated this stupendous phenomenon of the wind drift under the expression "the centrifugal broom." What it accomplishes is not overlooked by any explorer of either the Greenland or the Antarctic continental glacier. The experience of Shackleton above cited is in point, but let me cite three other explorers, each of them of vast experience and two of them on the Greenland glacier. Peary wrote in 1898:

> There is one thing of special interest to the glacialist—the transportation of snow on the ice-cap by the wind. No one who has not been there can have any conception of its magnitude. The wind is always blowing, and blowing almost always on lines which would be gravity lines from the interior. . . . . I have walked for days in an incessant sibilant drift of flying snow, rising to the height of the knees, sometimes to the height of the head. If the wind becomes a gale, the air will be thick with the blinding drift to the height of 100 feet or more. I have seen in the autumn storms in this region, round an amphitheatre of some 15 miles, snow pouring down in a way that reminds one of Niagara. When it is remembered that this flow of the atmosphere from the cold heights of the interior ice-cap to the lower land of the coast is going on throughout the year with greater or less intensity, and that a fine sheet of snow is being thus carried beyond the ice-cap to the ice-free land at every foot of the periphery of the ice-cap, it will perhaps be seen that the above assumption is not excessive.[15]

[15] "Journeys in North Greenland," *Geog. Jour.*, Vol. XI (1898), pp. 233–34.

In 1915 Knud Rasmussen wrote that "the marginal portions of the glacier were subject to continual storms, with the wind descending the slopes and filling the air with drift-snow."[16]

Sir Douglas Mawson wrote in 1914 concerning conditions at his base on the Antarctic Continental Glacier near its margin:

> . . . . We led a strenuous existence at winter quarters, buffeting with a sea of drifting snow which poured fluid-thick over the landscape. . . . .
>
> For months the drifting snow never ceased, and intervals of many days together passed when it was impossible to see one's hand held at arm's length. . . . . Such weather lasted almost nine months of the year.[17]

Since this drift snow moves always outward from the central area and supplies most of the snow which reaches the glacier surface outside that central area, it must be assumed to shape largely the glacier's flatly domed surface, except in so far as outward flow enters for the marginal zone, and, in shaping the surface, it must be assumed to supply material to make up for any waste in the interior which is due to the outward flow within the marginal zone.

By far the greater portion of this drift snow is carried to the front, where in the winter season there accumulate deep deposits which have been described by Chamberlin for the northwest coast as "fringing glaciers," and by Wegener for the northeast coast as "snowdrift glaciers."

THE COLD INTERIOR REGION OF STRONG RADIATION

DISCOVERED BY EXPLORERS

Already as far back as 1920, when reporting officially on his crossing of the

[16] *Med. om Grönland*, Vol. LI (1915).

[17] "Australasian Antarctic Expedition, 1911–1914," *Geog. Jour.*, Vol. XLIV (1914), p. 269.

inland ice in the summer of 1912, Alfred de Quervain described the wind system above it:

> . . . . It appears as if the air was streaming out after the manner of a liquid from the interior down the inclined slopes toward both coasts. . . . .
>
> Such a determination, even for summer conditions, gives support to the assumption of a very marked inland-ice anticyclone in the sense of the interesting demonstrations of W. Hobbs [in *Existing Glaciers*]. Our advance results have therefore given added value to these views.[18]

Of the central area of the ice cap (Fig. 7) and its sharply defined boundaries his description is now a classic:

> This central cold region is very strikingly set off from the marginal zones. In the first 13 days of the advance . . . . the mean value of the temperature amounted to −0.85° [C.] from which the daily means ranged only 1–2°; a progressive fall is scarcely indicated. On July 3rd at 1936 m. we entered suddenly into a cold region which in time stretched out for 13 days and in space over the maximum elevation (2500 m.) until we had reached the elevation of 2250 m. on the descent. Within this cold region the daily mean of the temperature amounted to −10.0° and ranged on the average not more than ±1.6° from it; . . . . Most abruptly then, during the last five days of the transection, beginning in 2250 m., the temperature went up and amounted in the mean for this period to −0.02°. . . .[19]

The sharply defined margins of this cold interior region were further made known by Koch and Wegener on the basis of Fridtjof Nansen's[20] and their own observations,[21] and they prepared a crude sketch map of the interior area (Fig. 8 *at left*). Making use of the material now available,[22] I have given with somewhat greater precision the boundaries of the cold interior region (Fig. 8 *at right* and Fig. 1).

At my request Dr. Belknap has plotted his daily temperature observations en route to, and while at, Camp Watkins (Fig. 9). The other pertinent records as assembled by Koch and Wegener are reproduced in Figure 10.

On the basis of the then available material, I outlined in *Glacial Anticyclones* (1926) the characteristics of the Greenland interior region, though these were known only for the months of summer and early fall. As compared with the surrounding zone, these were (1) a markedly lower air temperature but greater daily temperature range; (2) lower wind velocity and more variability of wind direction; (3) a deposit of fine, dry snow from a few inches to a foot in depth

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[18] *Ergebn. der Schweizerischen Grönlandexpedition 1912–13, Denksch. d. Schweiz. Naturf. Gesellsch.*, Vol. LIII, p. 113.

[19] *Ibid.*, p. 117.

[20] Nansen, who crossed Greenland in 1888, noticed the marked drop in temperature within the central area but had ascribed it to weather change.

[21] J. P. Koch and A. Wegener, "Wissenschaftliche Ergebnisse der dänischen Expedition nach Dronning Louises-Land und quer über das Indlandeis von Nordgrönland 1912–13 unter Leitung von Hauptmann J. P. Koch," *Med. om Grönl.*, Vol. LXXV (1930), p. 550, Fig. 287.

[22] Alf Maurstad, "Die meteorologischen Beobachtungen während Arne Høygaard and Martin Mehrens Durchquerung von Grönland 1931," *Geofysiske Publikasjoner* (Oslo), Vol. IX, No. 10, pp. 1–11; S. T. A. Mirrlees, "Meteorological Results of the British Arctic Air-Route Expedition 1930–1," *Meteor. Office, Geophys. Mem. No. 61* (1934), pp. 1–61; Martin Lindsay, Sledge, Cassell, p. 342, map and illustrations (1935). See also "The British Trans-Greenland Expedition, 1934," *Geog. Jour.*, Vol. LXXXV (1935), pp. 393–411 and Vol. LXXXVI (1935), pp. 235–52; Johannes Georgi, *Mid-Ice* (London, 1934), pp. 71–83; and also *Wissenschaftliche Ergebnisse d. deutsch. Grönland-Expedition Alfred Wegener 1929 und 1930–1931*, ed. Kurt Wegener, Vol. IV, Part II: *Meteorologie* (1939), pp. 191–386; Paul E. Victor, *La Géographie*, Vol. LXVII (1937), pp. 33–37; also *My Eskimo Life* (trans. by J. Godefroi) (New York: Simon & Schuster, 1939), p. 349; R. L. Belknap, "Meteorological Report of the University of Michigan–Pan American Airways Greenland Expediton August 1, 1932—July 31, 1933, *Repts. Greenland Expeditions Univ. of Mich.*, Vol. VI, Part II (Ann Arbor: University of Michigan Press, 1941), pp. 157–97.

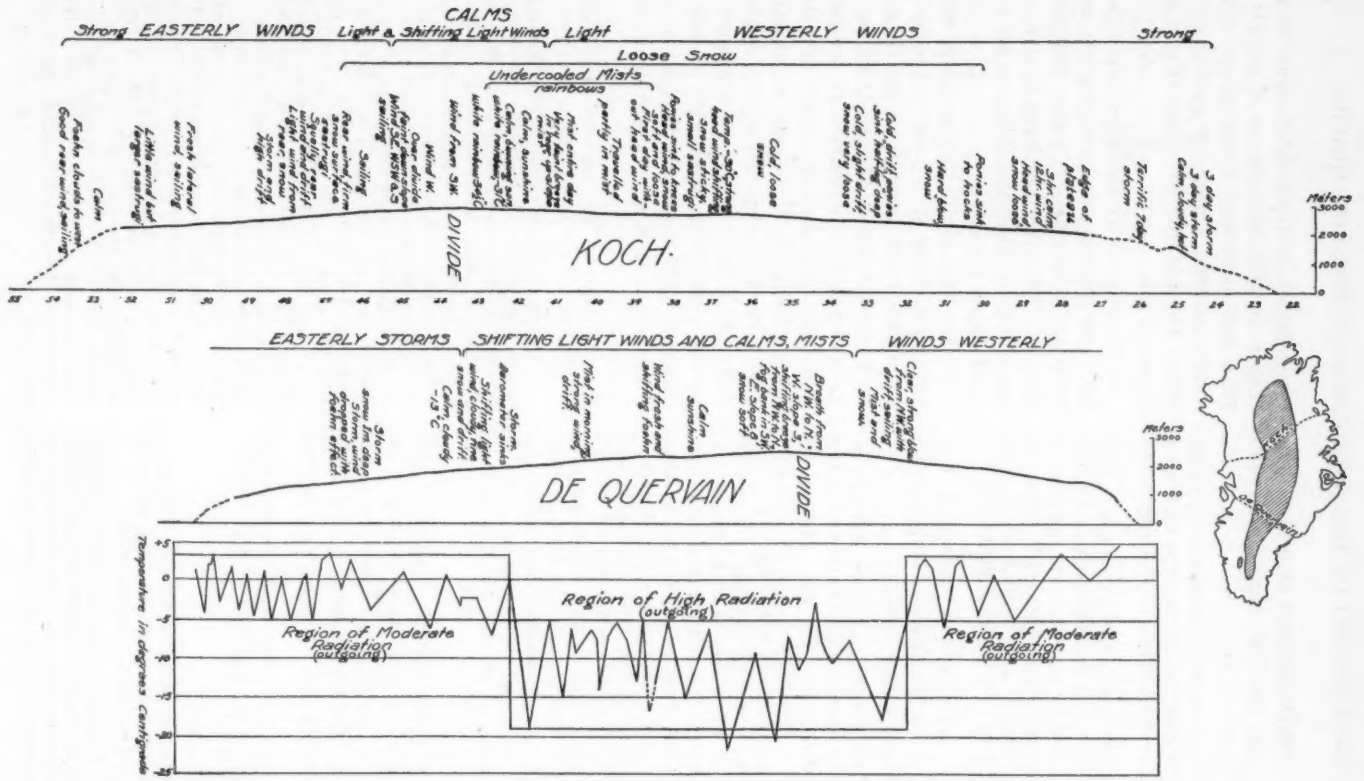

FIG. 7.—Profiles across Greenland to illustrate meteorological conditions as known in 1926 (from *Glacial Anticyclones*)

usually present; (4) precipitation of snow and of ice crystals from near-surface air layers; and (5) fogs, mists, halos, rainbows, and other optical phenomena.

1. *Temperature.*—This has already been referred to in considering De Quervain's transection of the area. Quite as striking in his profiles as the low temperatures and constancy of the daily temperature means was the large daily range of temperature (see Fig. 10). During each of the eleven days spent in crossing the interior region, the diurnal temperature range was close to 10° C. (average 10.6°), though while crossing the surrounding zone this range was about half that value; on the western flank, 5.5° C.; and, on the eastern flank, 6.0° C. Much the same was true on the transections by Nansen and by Koch and Wegener (see Fig. 10).

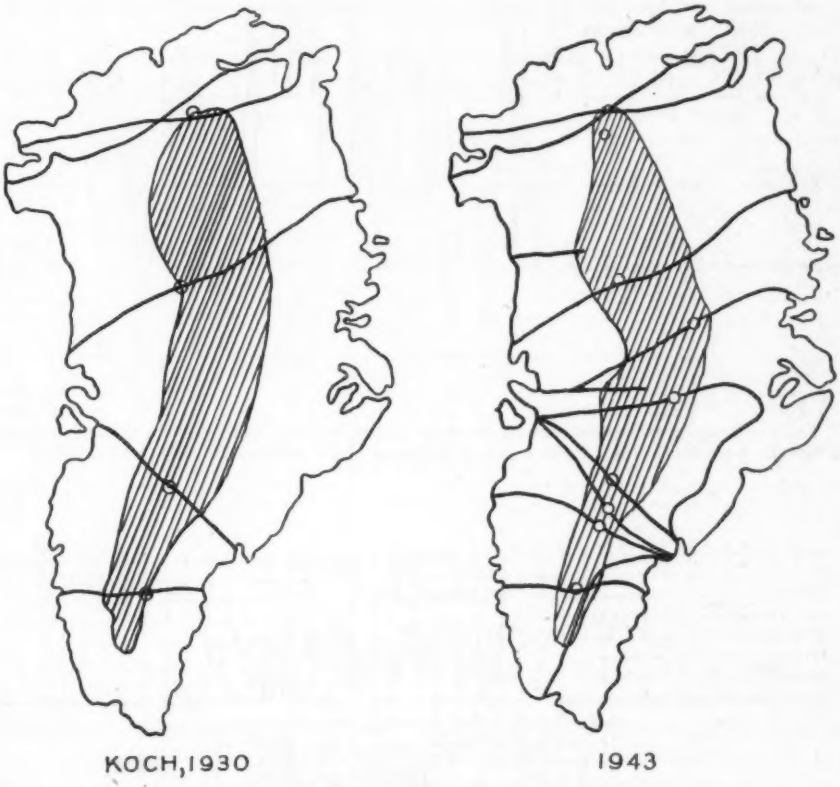

FIG. 8.—Maps of the cold interior region of Greenland

Today we have available temperature data from three stations, all located within the interior region and each with comparative data from its own control station near the coast in about the same latitude. Monthly averages are given in Table 1.

The notably lower temperatures registered at Eismitte over those from the

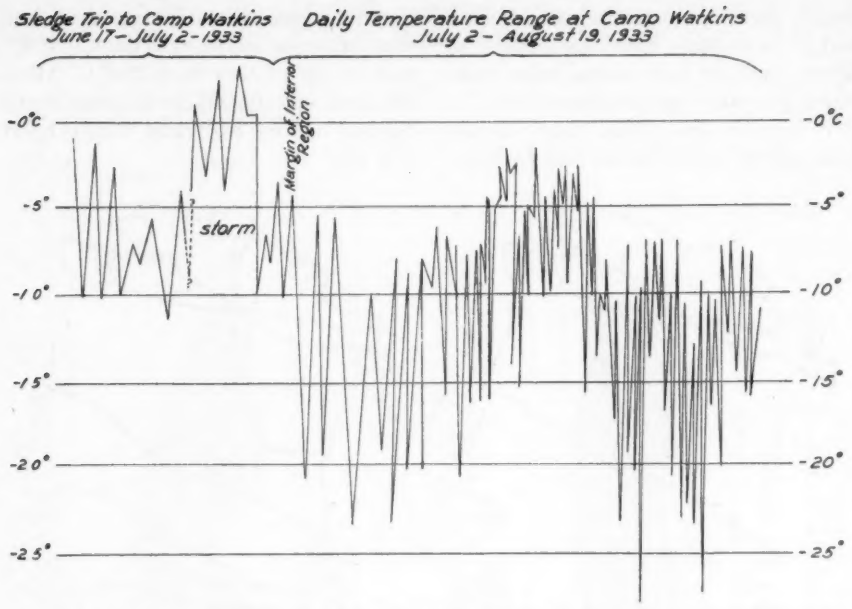

FIG. 9.—Temperature records made on the sledge journey to Camp Watkins in 1933 and at the station to show the border of the cold interior region. Contributed by Dr. Belknap and not before published.

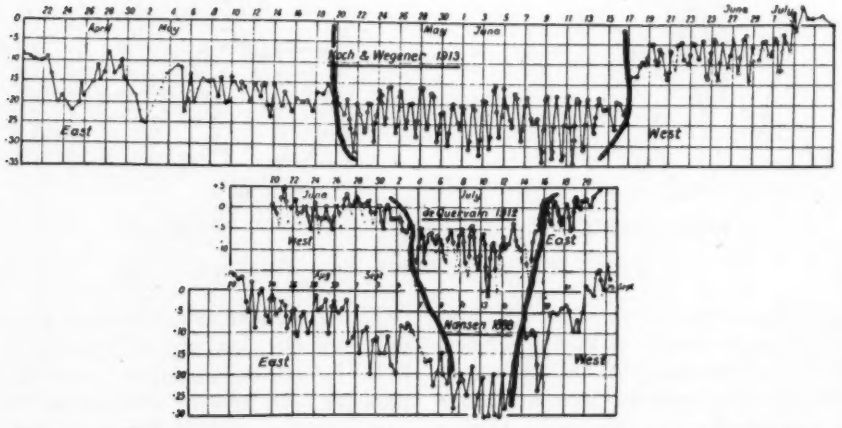

FIG. 10.—Profiles of daily temperature records made during transections of the Greenland inland ice (After Koch and Wegener.)

British Ice-Cap Station are explained in part by the higher latitude (4.5°) and in part by the longer period of the sun's absence, for the incoming solar radiation in part counterbalances the outgoing radiation. Somewhat similar differences characterize the marginal stations.

an entire year. At Weststation the mean annual wind velocity was 6.0 m.p.s. (25 miles per hour), and at Eismitte 4.6 m.p.s. (12 miles per hour), the difference being accounted for largely by the fall and winter months. Table 2 gives the monthly means in m.p.s.[23]

TABLE 1

MEAN MONTHLY AIR TEMPERATURES IN DEGREES CENTIGRADE

Month	Cold Interior Region			Inland Ice Margin		
	British Ice-Cap Station	Eismitte Station	Camp Watkins Station	British Base Station	Weststation	Peary Lodge Station
	1930	1930		1930	1930	1932
August	.....	−17.4°	.....	+6.0°	− 0.4°	+ 3.6°
September	− 1.7°	−21.6	.....	+8.0	− 3.5	+ 0.7
October	−27.2	−34.7	.....	−1.5	−13.1	− 4.9
November	−33.9	−43.2	.....	−5.9	−17.9	−12.6
December	−31.1	−38.5	.....	−6.0	−19.4	−16.4
	1931	1931	1933	1931	1931	1933
January	−30.6°	−40.5°	.....	−7.6°	−16.3°	−24.3°
February	−36.1	−47.9	.....	−9.5	−24.0	−17.1
Average	−26.7°	−37.7°	.....	+0.3°	−13.5°	−14.0°
March	.....	−40.3°	.....	−7.6°	−22.8°	−18.7°
April	.....	−31.0	.....	−2.0	−16.0	−15.4
May	.....	−20.3	.....	+0.3	− 4.6	− 5.1
June	.....	−15.6	.....	+5.2	+ 0.8	+ 2.1
July	.....	−11.2	−9.0°	+7.5	+ 2.7	+ 7.0
	.....	−30.2°	.....	−2.0°	−11.2°	−10.0°

2. *Wind force and direction.*—Wind velocities within the interior region are considerably less than in the exterior zone, and wind direction less constant; though for both in the light of the extensive body of new data the known contrasts are somewhat less pronounced than they were when our knowledge was restricted to brief periods and exclusively summer observations.

In latitude 71° the two German meteorological stations located, respectively, in the interior at Eismitte and on the glacier near the west coast at Weststation, permit of a comparison throughout

At the British stations located in latitude 66.5° during the same year their Ice-Cap Station was occupied for seven winter months, September to March, and comparison of the winds there with those of the Base Station near Angmagssalik indicate more light and moderate winds in the interior region, with both more calm periods and more fierce storms at the coast, the calms probably explained by overriding (Fig. 12).

The monthly averages of wind velocity and the number of storms as averaged

[23] Wegener, *Repts.*, Vol. IV, Part II, p. 202, and Vol. VII, p. 5.

between arbitrary limits hardly tell the whole story. It is the last double column in Table 3 which is of greatest interest in this comparison, for, whereas there were but 9 storms at Ice-Cap Station of force 8 (38 miles per hour) or greater, at the Base Station there were 20; and though the greatest wind on the ice cap was of force 9 (47 miles per hour), at the base

TABLE 2

MONTHLY MEANS OF WIND VELOCITY

Month	Weststation	Eismitte
August	4.6	3.6
September	6.4	4.9
October	7.8	4.4
November	8.8	4.1
December	6.2	6.1
January	8.9	4.7
February	6.4	4.0
March	5.5	5.7
April	5.1	5.3
May	4.2	4.2
June	4.1	3.9
July	4.1	4.2
An. mean	6.0	4.6

besides 1 of force 9, there was 1 of force 10 (55 miles per hour), 3 of force 11 (64 miles per hour), and 7 of force 12 (75 miles per hour).[24] For similar contrasts at the German stations see Table 6, p. 93.

Evidence of the greater variability of wind direction for the interior region is supplied by the records at Eismitte. The station was located probably a hundred miles to the west of the ice divide, and there was a preponderance of surface winds from the southeast, but most other directions were also represented. The pilot-balloon ascents carried out during the summer indicate that shifting winds also extend up from the surface.[25]

[24] Mirrlees, *op. cit.*, p. 14.

[25] Wegener, *Repts.*, Vol. IV, Part I, chart in pocket.

3. *Surface-snow deposit.*—All explorers who have crossed the interior region of the ice cap have drawn attention to the deposit of very fine and dry mealy snow which for most of the time is to be found on the surface. The particles of snow have been described as so fine as to be pressed into the pores of the skin. In this deposit the fresh tracks of men, dogs, and sledges are retained. By contrast, within the exterior area the surface, when not obscured by the ever present drifting snow, there is hard snow packed by the wind and creased by the *sastrugi* in the direction of the prevailing downslope storms. Even heavily laden sledges leave little trace on this surface.

4. *Snow precipitation.*—Records of the ice-cap stations are in agreement in showing that the cold interior region is the locus of glacier nourishment which supplies that stupendous quantity of drift-sweepings over the exterior zone that build up the marginal deposits and stagger the imagination of every explorer. The figures are given in Table 4.

5. *Fogs and mist, rime, halos, parhelia, white rainbows, etc.*—All explorers who have crossed the interior region have drawn attention to these condensation and resulting phenomena. Rime forms not only around the face, where the breath figures, but on sledges and other equipment. Mock suns and white rainbows are common, owing to the ice spicules and water droplets within the air layers close to the surface even during clear sky conditions.[26] The relative humidity is always high in Greenland because of the low temperature. The mean annual value for Eismitte is 81 per cent, as against 79 per cent at Weststation.[27]

[26] Sunshine hours per month at Eismitte for the ten months (except December and January) averaged 241 as against 229 at Weststation.

[27] Wegener, *Repts.*, Vol. VII (1940), p. 20.

Much more significant is the vapor pressure, and this at Eismitte, even in the monthly mean, occasionally exceeded by 15 per cent the normal figure for its value above an ice surface. This supersaturation permits the sublimation and separation of ice spicules over the surface which in character are similar to those observed from aircraft which have invaded the cirrus clouds.

TABLE 3

NUMBER OF STORMS (BEAUFORT SCALE)

Month	Calms		1–3		4–7		8–12	
	Ice-Cap	Base	Ice-Cap	Base	Ice-Cap	Base	Ice-Cap	Base
September	1	53	95	46	4	1	0	0
October	0	44	83	48	17	4	0	4
November	6	45	66	40	28	8	0	7
December	2	79	70	16	28	5	0	0
January	1	57	73	16	21	15	5	12
February	2	49	65	27	30	7	3	17
March	7	74	62	18	30	2	1	6
Total	19	401	514	211	158	42	9	46

TABLE 4

SNOW PRECIPITATION AND SNOW DRIFT WITHIN THE INTERIOR REGION

Station and Observer	Precipitation (in Days)	Drift (in Days)
Eismitte (Georgi)*	213 out of 365; 58 per cent of all	191 out of 365; 52 per cent of all
Ice-Cap (Courtauld)†	57 out of 184; 31 per cent of all	23 out of 184; 12½ per cent of all
Camp Watkins (Belknap)‡	22 out of 49; 45 per cent of all	13 out of 49; 27 per cent of all

* J. Georgi, *Wiss. Ergeb., etc.*, Vol. IV, Part I, chart in pocket.

† S. T. A. Mirrlees, "Meteorological Results of the British Air-Route Expedition in 1930–31," *Meteor. Office, Geophys. Mem. No. 61* (1934), pp. 36–61. The station was, unlike the other two, located close to the divide, which explains the lower drift value.

‡ Contributed by Dr. Belknap for this report and not before published.

THE MOTIVATION OF THE GLACIAL ANTICYCLONE

The initiation and maintenance of the glacial anticyclone was explained by refrigeration due to excessive outgoing radiation within the interior region of Greenland. This has now been confirmed by the studies made at Eismitte. In his summing-up of the principal scientific results, Dr. Kurt Wegener states:

As the model examples of the "glacial anticyclones" for all seasons can serve the South Polar region and Greenland. Greenland lies close to the European culture and it therefore appeared to be an essential problem of the expedition to investigate the so-called "glacial anticyclone" of Hobbs. . . . .

The statistical data show us that we have in fact to do at the level of the sea with a "high pressure region" from which toward all sides air is streaming out. In the ordinary moving high pressure region the troposphere is lifted up far into the stratosphere, the pressure and the temperature above the heart of the high pressure area in consequence of the inertia is higher than the troposphere in the surrounding region (*Nachbarschaft*). On the other hand, the physical explanation for the "glacial high pressure region" is provided by the outgoing radiation from the surface. The cold and low-moisture air of the polar region is, in contrast with the air of our latitudes, very permeable to long (warm) radiant waves. The névé cover of Greenland therefore sends out radiation in ex-

change with interplanetary space and the high layers of the stratosphere, and cools itself off to a radiation equilibrium with the higher strata of the atmosphere and the sky.[28]

Kurt Wegener then proceeds to explain the glacial anticyclone as a reaction *between the inland ice as a whole and the surrounding sea*, instead of between the cold interior and the surrounding zone where the striking contrasts are to be found. Nowhere in the Wegener reports

TABLE 5

CLOUD COVER OVER GREENLAND

Explorer	Exterior Region	Interior Region
Nansen, 1888	6.6 (Aug.–Sept.)	4.0 (Sept.)
De Quervain, 1912	6.0 (June–July)	3.5 (July)
Koch and Wegener, 1913	4.4 (April–July)	2.5 (May–June)
Mean	5.7	3.3
Eismitte Station, 1930–31*		5.6 (Entire year)
Ice-Cap Station, 1930–31		4.1 (Sept.–March)

* The hours of sunshine at Eismitte for the months August–November, 1930, and February–July, 1931 (10 months), were 2,418. The clouds were the high types, cirrus either typical or in combination 52½ per cent, alto-cumulus 33⅓ per cent, and strato-cumulus 15 per cent. Cumulus clouds were absent.

is the interior region discussed, though the original director of the expedition was, with J. P. Koch, the first to define its boundaries (see p. 85 and Figs. 7–10).[29]

As yet we have been without any wholly satisfactory station within the exterior region for registering the daily course of the weather units,[30] though the records of coastal stations may at times be drawn upon for pressure and wind velocity. In considering the distribution of cloud cover, we must perforce make use of explorers' observations during transections. Those available are entered in Table 5. From these data it is clear that the interior region has the advantage over the surrounding region in its outgoing radiation.

THE INTERIOR REGION THE PULSING HEART OF THE GLACIAL ANTICYCLONE

The greatest contribution of the Wegener expedition has been the chart setting forth the daily registration of meteorological units at Eismitte. From this chart it appears that pressure, temperature, and wind force are all regulated by the outward radiation, controlled throughout, as this is, by the nebulosity, the screen of the cloud cover. So delicate is this adjustment that any increase in the cloud cover is almost immediately followed by a rise in air temperature, while a clearing of the sky results in a sudden drop in temperature. The chart is so large, nearly 4 feet in length, that it cannot be reproduced here, but it should be studied by every student of continental glaciation.[31]

THE CONTRASTED SEASONS OF THE GLACIAL ANTICYCLONE

Another very important revelation of the Georgi chart is that the Greenland anticyclone has two sharply contrasted

[28] *Ibid.*, p. 28.

[29] More even than has been generally realized, the death on the ice cap of Dr. Alfred Wegener was a major loss to science. In place of the very able and experienced second-in-command, Dr. Johannes Georgi, director at Eismitte, outstanding scientist with years of experience in Greenland and a close intimate of the lost leader, Berlin appointed as successor in command the strong Nazi party man, Dr. Kurt Wegener, who though a brother was without Greenland experience. He refused to permit Dr. Georgi to express any conclusions upon his research, taking upon himself that office, with results that might have been expected. Georgi's report contains, therefore, his data only.

[30] Weststation was on the edge of the track for summer cyclones.

[31] Johannes Georgi, *Die Eismitte Station, Wissenschaftliche Ergebnisse der deutschen Grönland-Expedition Alfred Wegener 1929 und 1930/1931*, Vol. IV, Part I, chart in pocket ("Täglicher Verlauf der Witterungselemente für Eismitte vom 1. August 1930 bis 7. August 1931").

seasons. These are a short summer of but four months (in the year 1930–31 from May 18 to September 17) and a long winter of eight months (in the year 1930–31 from September 18 to May 17). The contrasts of the weather elements for these seasons are displayed in three sections of the chart, the middle one from one of the "transition" periods (Fig. 11).

TABLE 6

SEASONAL VALUES OF WEATHER UNITS AS REGISTERED AT EISMITTE

Month	Cloud Cover (in Tenths)	Days with Snow-fall	Days with Drift	Wind Force (m.p.s.)	Wind Force (m.p.s.) West-station
Summer:					
May (last third)	6.1	10	5	6.5	.....
June	5.0	14	14	3.9	4.1
July	4.6	23	20	4.2	4.1
August	6.0	19	6	3.6	4.6
September (first two-thirds)	3.9	4	6	5.0	.....
Average or total	4.0	70	51	3.5	.....
Winter:					
September (last third)	8.0	11	8	6.3	.....
October	5.5	19	12	4.4	7.8
November	4.8	13	14	4.1	8.8
December	5.2	13	24	6.1	6.2
January	5.6	18	18	4.7	8.9
February	4.8	16	16	4.0	6.4
March	5.7	14	16	5.7	5.5
April	6.5	25	23	5.3	5.1
May (first two-thirds)	7.0	14	9	5.6	.....
Average or total	5.5	143	140	4.4	.....

This chart reveals, then, after the manner of a cardiogram the beating heart of the glacial anticyclone, the source of the pulses[32] which, emanating from this central region, go out over the exterior zone to the margin of the ice and far beyond. Whereas in summer these pulses are relatively weak, as indicated especially in the temperature, and have a period of perhaps three days on the average, the winter pulses are very strong and tend to have a period on the average of about eight days. While their occurrence is not strictly periodic, there is certainly an approach to periodicity.

From Georgi's chart also it is possible to compare weather elements of the summer with those of winter (Table 6), though not in a revealing manner because we have no data on the *amounts* of snowfall and drift. We know from explorers' observations and from the experience of the inhabitants of the "colonies" on the coast extending through two centuries that most of the snow drift, and practically all the *effective* snow-drift accumulation there, takes place in the winter season. This fact does not emerge in the mean values of Table 6 but does in the character of the chart of daily registrations (Fig. 11).

THE STRUCTURE OF THE GREENLAND ANTICYCLONE

The aerological work of the University of Michigan expeditions showed that on the west coast of Greenland (in all five stations distributed from Ivigtut in latitude 61° to Peary Lodge in latitude 74.5° N.), the outflowing air of the glacial anticyclone extends as a rule up to levels of 3,000 meters and more above sea. Starting from the interior region and coming down the west slopes of the inland ice, this wind is deviated through the influence of earth rotation and reaches the ice margin from the east-southeast. Going up from the surface, wind is found to be deviated clockwise until it comes from a southerly direction.

The Michigan observations are in this respect apparently confirmed by those of the Wegener Expedition. Dr. Kurt Wegener in his report differentiates a lower air layer 400 meters in thickness, which he describes as "cold air" or "heavy air," on the basis of the observations at Eismitte and the coastal stations of the

[32] In *Glacial Anticyclones* I used the term "strophs" for these heartbeats, and at times in this article I have employed the term "surges"; "pulses" is probably, of all, the most appropriate.

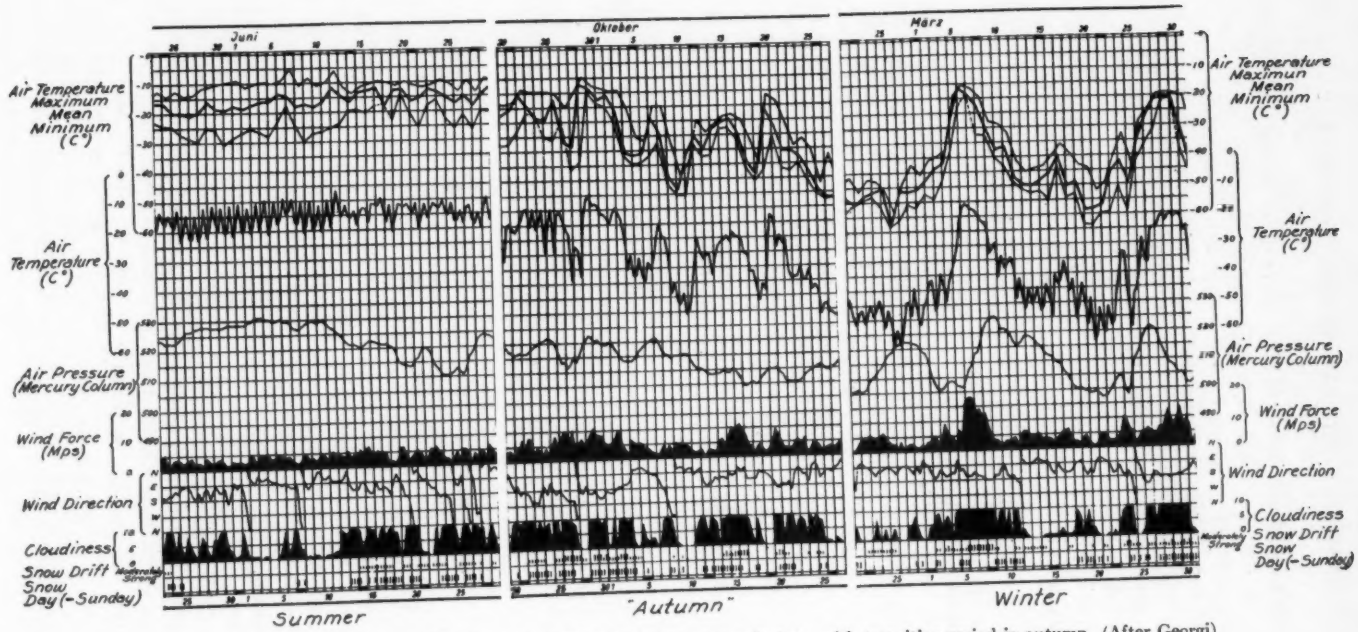

FIG. 11.—Daily course of the weather elements at Eismitte for summer and winter with transition period in autumn. (After Georgi)

expedition, with higher velocity outflowing currents extending up to 3,000 and 4,000 meters. As regards the instreaming currents above the outflowing air, the director states:

> When the air layer streaming toward the inland ice arrives in levels of 4,000 to 8,000 m. it is ten times as powerful (*mächtig*) as the heavy air, the velocity of which is only a tenth, or around 4 mps. . . . . Furthermore, conjecturally, the (higher) wind streams in predominantly from the north and northwest.[33]

This corresponds throughout with the observations carried out for two years

nection with the retreat of the glacier front as determined by Lauge Koch and others, must be taken to indicate that the inland ice of Greenland is today undernourished and shrinking in dimensions. As already noted, the summer cyclones now invade the glacier from the west in southwestern Greenland for a maximum distance of some tens of miles, and in the elevation of 1,500 meters they liquidate each summer an ice layer about 10 feet in thickness, and this is in addition to the snow outsweepings of the preceding winter.

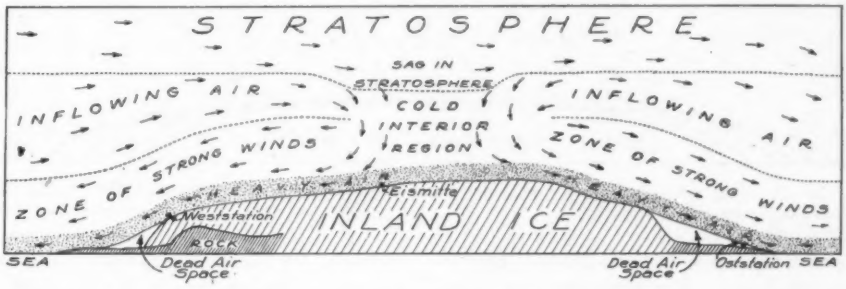

FIG. 12.—Profile of the Greenland glacial anticyclone along an east-west line through the German stations in latitude 71° N.

continuously at Mount Evans.[34] The structure of the Greenland anticyclone is represented in Figure 12.

PRESENT CONDITION OF THE GREENLAND ANTICYCLONE ONE OF UNDERNOURISHMENT

Today the vast quantity of drift snow is carried out to the margins of the glacier. In southwestern Greenland, at least, it is completely melted by early summer; and this fact, when considered in con-

Recent study of the deposits of the Pleistocene continental glaciers of North America seems to show that progressive invasion from summer cyclones reaching the glacier from the west causes the gradual dissolution of glaciers of continental type during a receding hemicycle of glaciation.[35]

As the receding hemicycle continued, the vigor of the glacial anticyclone waned, and the cyclones which arrived from the west invaded the glacier to greater and greater distances with the consequence that its upper surface low-

[33] *Repts.*, Vol. VII, p. 31.

[34] *Repts. of the Greenland Expeditions of the University of Michigan* ("Univ. of Mich. Studies: Scient. Ser.," Vol. V, Part I [1931]), pp. 225–39.

[35] William H. Hobbs, "The Glacial Anticyclone and the Continental Glaciers of North America," *Proc. Amer. Phil. Soc.*, Vol. LXXXVI (1943), pp. 368–402.

ered and in lesser measure its front retreated. The moderate rains from such invasion increased the quantity of melt water which issued from the western front, but laid down considerable outwash deposits only if and when the lowered upper surface had reached to the bottom layers with their englacial material.

When the cyclone invasion from the west had reached the divide of the glacier, a new condition was suddenly inaugurated, now that the outflowing winds of the glacial anticyclone no longer were directed in opposition to the advance of the cyclones. The incoming air mass from the west therefore rose over the cold anticyclonic air, and very copious rainfall took place. These rains descended on the glacier's eastward slopes, and a stage of relatively rapid liquidation began. Hence invading and later transecting cyclones, instead of nourishing continental glaciers, bring about their extinction, at first relatively slowly during the stage of invasion of the western slope, but later rapidly so soon as the stage of cyclone transit has opened with the crossing of the divide.

MANNER OF EXTENSION OF CONTINENTAL GLACIERS IN THE ADVANCING HEMICYCLE OF GLACIATION

Since neither of the two existing continental glaciers is to be observed in an advancing hemicycle and, further, since the earlier ones have left us records largely from their receding hemicycles, for a study of the continental glaciers in their advancing hemicycles we are thrown back on inferences from the behavior of the existing examples during the receding hemicycle. The centrifugal broom of the glacier distributes the nourishment supplied largely in the cold interior region and also shapes the surface. It piles up the major portion of the drift snow outside the margins, but with much thinner deposits over its upper surface (Fig. 13). In this stage of the advancing hemicycle annual layers will be added to the glacier over most of its surface, and it is probable that the layers measured by Sorge in the shaft at Eismitte stem from this earlier period.[36] No proof has been supplied that they are of recent deposition.

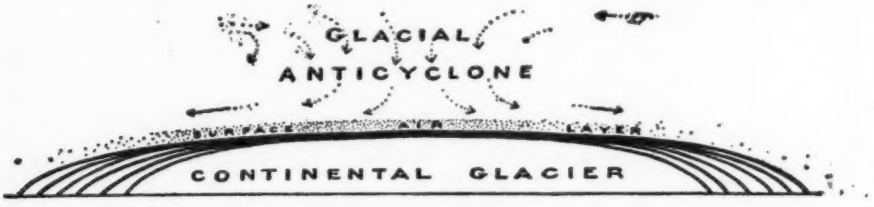

FIG. 13.—Diagram to illustrate the probable manner of growth and of marginal extension of a continental glacier in the advancing hemicycle.

[36] *Repts.*, Vol. IV, Part II, pp. 348 ff.

MIDDLE ORDOVICIAN OF CENTRAL PENNSYLVANIA

G. MARSHALL KAY
Columbia University

PART II. LATER MOHAWKIAN (TRENTON) FORMATIONS*

NEALMONT LIMESTONE

DEFINITION AND DISTRIBUTION

The Nealmont limestone[50] (village, Blair County, 2 miles east of Tyrone) is 135 feet thick in the type section at Union Furnace. The base is a 3-foot ledge of dark, coarse-textured, impure limestone disconformably overlying the Stover limestone (Table 4 and Fig. 11); the top, a thick ledge of dark, brown-weathering, fossiliferous limestone underlying the basal cobbly beds of the Salona formation. It is the upper part of the "Lowville" and the succeeding Rodman in the section of Butts for the Tyrone quadrangle.[51]

The Nealmont is present in all belts of outcrop in central Pennsylvania; the Mercersburg limestone, at least partially equivalent, persists in the Cumberland Valley region. The distribution of outcrops does not permit definition of the whole form of the deposit, but the formation is from 125 to 145 feet thick in a belt from Antes Gap (145 feet [Fig. 13]), through Milheim (130), Naginey (135), Oak Hall (135), Union Furnace (135), and Williamsburg (125). Thickness diminishes by overlap (Fig. 14) to 50 feet (Bellefonte) to the northwest and to about 100 feet at Allensville and Blacklog to the southeast; and Nealmont and Mercersburg beds average about 50 feet in the Path and northwestern Cumberland valleys, the Mercersburg thickening to 200 feet southeastward.[52] Isopachs trend more northerly than the strike in the north, somewhat more southerly in the south; on a palinspastic base they are fairly rectilinear, trending north-northeast.

STRATIGRAPHY

The formation has fairly constant lithologic characters in the thicker sections. The type section for the members of the Nealmont is selected as that along Highway 322, a mile west of Tusseyville, 3 miles south of Centre Hall, and 6 miles east of Oak Hall. The lowest member is the Oak Hall (new; village east of State College, Centre County), composed of about 60 feet of heavy-ledged limestone, with metabentonites 18 feet from the top and at the top[53] (Table 7). The middle member, the Centre Hall[54] (village, Centre County), consists of more fossiliferous, interbedded shaly and heavy-ledged lime-

* This article is a continuation of "Middle Ordovician of Central Pennsylvania, Part I: Chazyan and Earlier Mohawkian (Black River) Formations," published in Vol. LII, pp. 1–23.

[50] G. M. Kay, "Middle Ordovician of Central Pennsylvania" (abstr.), *Bull. Geol. Soc. Amer.*, Vol. LII (1941), p. 1969.

[51] Charles Butts, F. M. Swartz, and Bradford Willard, "Tyrone Quadrangle," *Pa. Geol. Surv. Bull. 96* (4th ser., 1939), pp. 22–23.

[52] L. C. Craig, "Middle Ordovician Limestone near Chambersburg, Pennsylvania" (abstr.), *Bull. Geol. Soc. Amer.*, Vol. LII (1941), pp. 1963–64.

[53] NOTE.—The symbols *N1* and *N2* for these clays are reversed in Fig. 2, p. 3.

[54] R. M. Field, "The Middle Ordovician of Central and South Central Pennsylvania," *Amer. Jour. Sci.*, Vol. XLVIII (4th ser., 1919).

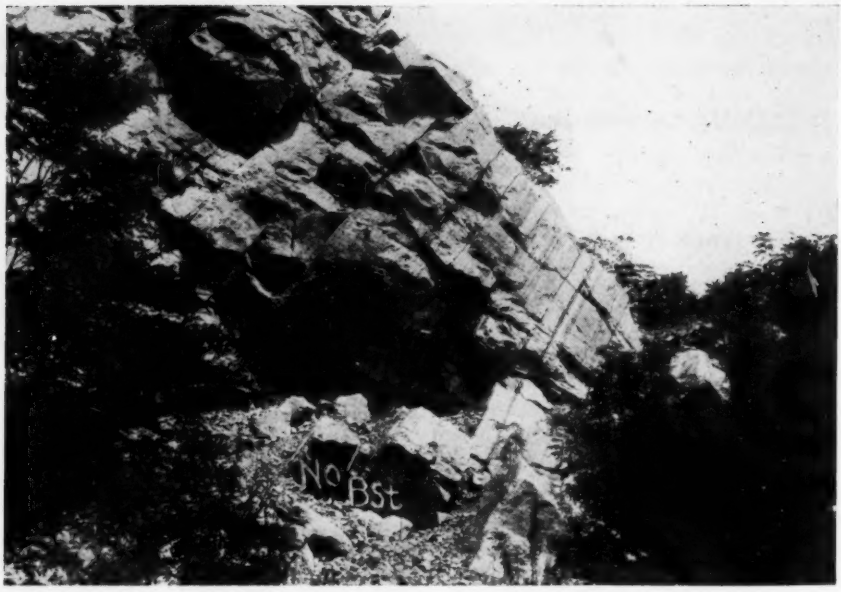

FIG. 11.—Nealmont limestone (*NO*) disconformably overlying Stover limestone of the Benner formation (*BSt*) in bluff west of Pennsylvania Railroad cut near Union Furnace; see Table 4.

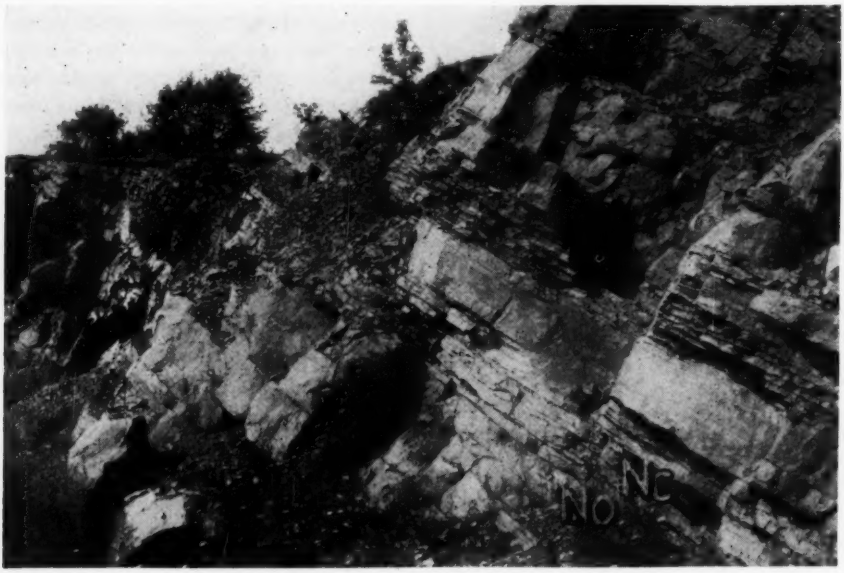

FIG. 12.—Quarry north of Centre Hall Station; Nealmont limestone, Centre Hall member (*NC*) overlying Oak Hall member (*NO*).

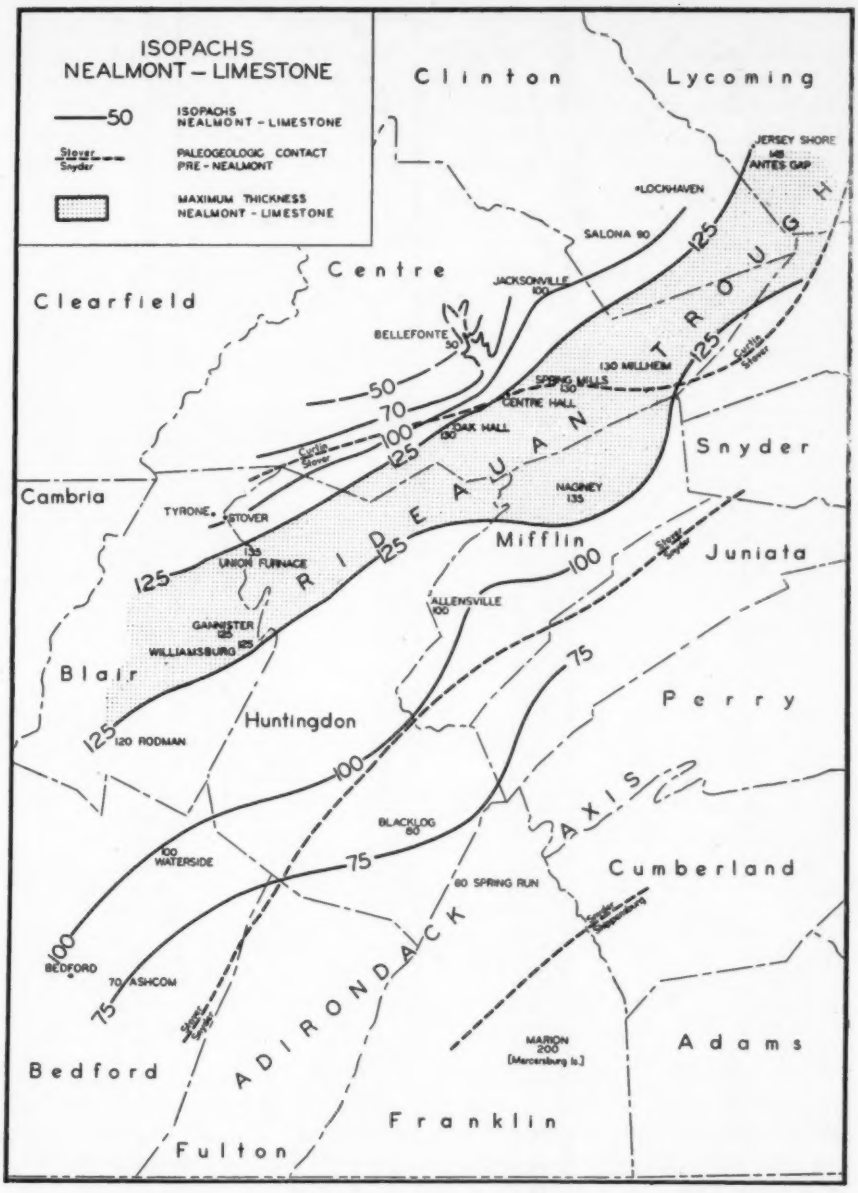

FIG. 13.—Isopachal map of the Nealmont limestone, with the underlying paleogeology; scale about 17 miles to one inch.

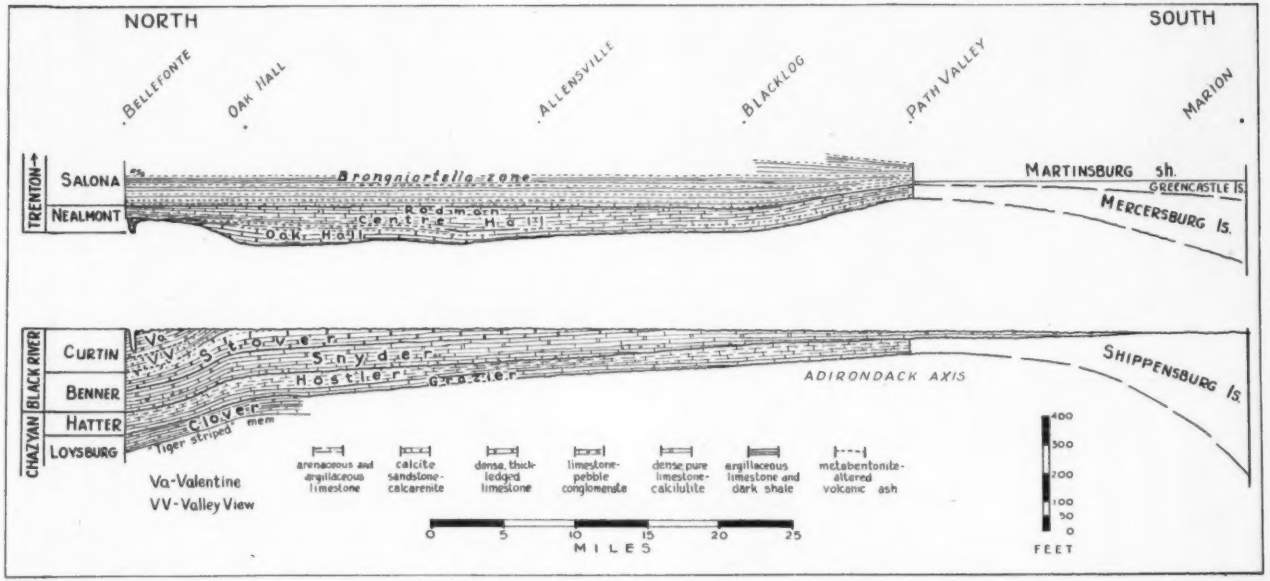

FIG. 14.—Restored sections of the Nealmont formation and the lower part of the Salona formation (*above*), and of older formations (*below*), from Bellefonte southward to Cumberland Valley.

stone, 44 feet thick (Fig. 12). As originally described, the "Center Hall" consists of "a narrow zone (about 40 feet) which occurs above the Valentine and below the highly fossiliferous and lithologically dissimilar Rodman" at Bellefonte; these beds lie disconformably on the Valentine in the Bellefonte section, the Oak Hall member being overlapped. The upper, the Rodman[55] (station near Roaring Springs, Blair County), has been defined as succeeding the Centre Hall and underlying the cobbly beds below metabentonite *o* of the Salona formation;[56] it is composed of darker, impure, brownish-weathering limestone, frequently having nodular chert in the lower part, and thin beds of white-weathering dense lime-

TABLE 7

NEALMONT LIMESTONE ONE MILE WEST OF TUSSEYVILLE

Description of Unit	Thickness	
	Of Unit	To Base Member
TRENTON group:		
Salona limestone:		
Black, dark-weathering, dense, argillaceous, plane-bedded, shaly limestone	.....	.....
Nealmont limestone:		
Rodman member:		
Dark, brownish-weathering, rather heavy-ledged, impure, fossiliferous limestone	18′	128′
Dark, somewhat impure, partially shaly limestone, with some black chert, and intercalated, mottled, white-weathering, platy limestone	8	110
Centre Hall member:		
Gray, medium-textured, shaly limestone with intercalated heavy, mottled ledges	44	102
Yellow clay, metabentonite *N2*	8″	.....
Oak Hall member:		
Gray, medium-textured, heavy-ledged limestone, somewhat fossiliferous	18	58
Yellow clay, metabentonite *N1*	6	.....
Gray, heavy-ledged, medium textured limestone, with some coquinal ledges near the base; top bed cherty	39	39
Contact not clearly exposed	.....	.....
BLACK RIVER group:		
Benner formation:		
Stover limestone:		
Gray, medium-textured, mottled limestone with intercalated calcarenite and thin limestone conglomerates; *Cryptophragmus* at 19 feet	26	.....
Brownish clay, metabentonite *F*	6	.....
Gray limestone like that above, *Cryptophragmus* 6 feet from top	.....	.....

stone; the thickness is about 30 feet in the type area, 26 feet in the section near Tusseyville. It has been stated that the name "Lemont" has been applied to units older than the beds, at the type section; the Lemont lime-

[55] Butts, "Geologic Section of Blair and Huntingdon Counties, Central Pennsylvania," *Amer. Jour. Sci.*, Vol. XLVI (4th ser., 1918), p. 526.

[56] R. R. Rosenkrans, "Correlation Studies of the Central and South Central Pennsylvania Bentonite Occurrences," *Amer. Jour. Sci.*, Vol. XXVII (5th serv., 1934), p. 115.

stone was originally defined[57] as "well-exposed in a railroad cut a short distance south of the town," west of Oak Hall. A species misidentified as *Maclurites "magnus"* Leseuer led to the classification as Chazyan and to the belief that it was older than the Curtin and

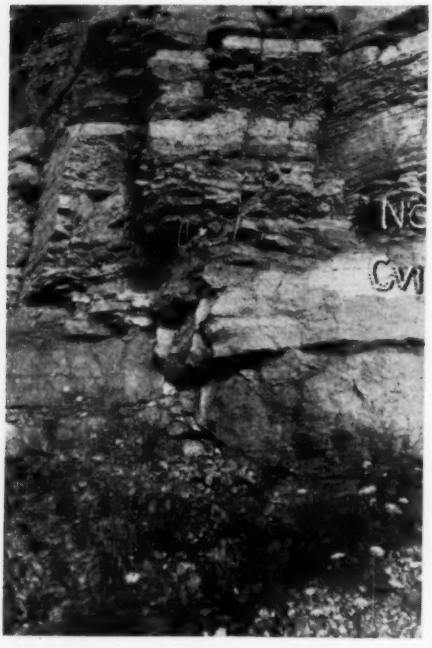

FIG. 15.—Quarry 21E, east of road north of Colesville; Nealmont (Centre Hall) limestone (*NC*) disconformably overlying Valentine limestone of the Curtin formation (*CVl*).

Benner limestones or "Lowville" in the Tyrone area; the fossil, *M. logani* Salter, is common in both Centre Hall and Oak Hall at Lemont.

The base of the Nealmont is commonly of dark, coarse-textured, impure limestone with *Columnaria* sp., the thickness variable from absence to 6 feet or more—normally a foot or two (Fig. 11). This lies upon a regional unconformity and is basal rather than synchronous, though of the Oak Hall member.

In the Bellefonte district the normal thickness of the Nealmont is about 50 feet, consisting of Centre Hall and Rodman members. But there is a great disconformity at the base of the limestone, which fills channels in the underlying Valentine limestone so as to gain a maximum of as much as 90 feet. The relations are best shown in the quarries west of the Pennsylvania Central Railroad[58] and of the road north of Colesville. In the first, the Valentine is but 17 feet thick, the top surface having relief of more than 4 feet at a single place. The base of the Nealmont is of 32 feet of coarse-textured, very heavy-ledged, *Columnaria*-bearing limestone, succeeded by about 46 feet of interbedded shaly and heavier beds and 10 feet of impure Rodman limestone; the total of Valentine and Nealmont is about 110 feet, less than the 140 feet at Bell Mine, where the thicknesses are 91 and 48 feet.

The unconformity is better displayed in the quarry north of Colesville. East of the road, 4 feet of shaly Nealmont limestone lie on about 85 feet of Valentine (Fig. 15); to the west, a wedge of beds overlaps on the Valentine, entering below the continuing 4-foot shaly zone. At the south end of the quarry this wedge consists of 1 foot 6 inches of dark, impure, tough limestone, 7 feet 6 inches of calcarenite with *Columnaria*, 7 feet of light-weathering, platy, argillaceous-partinged limestone with desiccation fractures and flow-structures, and 18 feet of dark, rather dense, impure, heavy-ledged, stylolite-partinged limestone—a total of 33 feet. Inasmuch as the thickness of the Valentine, which has 12 feet

[57] Butts, p. 526 of ftn. 54 (1918).

[58] Kay, "Chemical Lime in Central Pennsylvania," *Econ. Geol.*, Vol. XXXVIII (1943), Fig. 6.

6 inches of abnormal fossiliferous, dense, intraformational conglomerate-bearing rock at the top, is but 46 feet, the total of the Valentine and wedge of Nealmont, 79 feet, is less than that of the Valentine to the north. Probably the channel fillings are about equivalent to the upper Oak Hill member, though not of the typical lithology.

The disconformity at Bellefonte is but a local manifestation of a major regional unconformity. The Nealmont lies on the Valentine member of the Curtin formation in the northwest (Fig. 15) and on the underlying Valley View member (Fig. 16) in the margining belt extending southeast to Lemont and Millheim (Figs. 13 and 14). It lies on the Stover member of the Benner, southeastward to the Kishacoquillas Valley (Fig. 11), on the thinning Snyder member, in Blacklog, Path (Fig. 17), and western Cumberland valleys. Farther southeast, the equivalent Mercersburg lies on the pre-Snyder Shippensburg limestone.[59]

The Oak Hall and Centre Hall members are readily separable in western Penns Valley, for the metabentonites in the upper Oak Hall are distinct at Oak Hall, and the upper is exposed along Highway 45, 3 miles northeast of Boalsburg. One, probably the lower, is poorly exposed in the interrupted section along the railroad just west of the highway at Old Fort, where it is within 30 feet of metabentonite *F* in the *Cryptophragmus*-bearing Stover limestone. However, although the lithologies and thicknesses at Spring Mills and a mile south of Millheim are as in the Tusseyville section, the clays have not been seen; thus they are not persistent within the immediate area. Where they are not distinct, as at Union Furnace, Royer, Covedale, Ganister, and Waterside, the contact between the heavier ledged Oak Hall and more shaly Centre Hall can be placed only approximately.

A single distinct metabentonite has been recognized 31 feet from the base of the formation in the quarry by the Bethlehem Steel plant at Naginey, underlying 12 feet of heavy-ledged, relatively pure limestone that is succeeded by shaly, fossiliferous beds; Rosenkrans[60] noted a second clay, evidently at the horizon of the base of the shales. There seems to be 43 feet of Oak Hall, succeeded by about 60 feet of Centre Hall and 30 of Rodman to the *Echinosphaerites*-bearing basal Salona at the top of quarry. To the southeast, in northern Grove (Binkley and Ober) quarry in Blacklog Valley, a single 8-inch clay is 29 feet above the base of the Nealmont; though the directly underlying beds are heavy ledged, there are *Sowerbyella*-bearing shales at the base of the formation. If this is the upper Oak Hall metabentonite, the lower has not been recognized. Another distinct clay is exposed 51 feet higher and is thought to be the Salona *o* metabentonite; *Echinosphaerites* is present above supposedly the same clay in the northwest end of the shallow quarry to the northeast beyond Blacklog Creek. In the Path Valley a very thick clay is exposed about 8 feet from the base of the Nealmont in several sections, as in that at the limekiln a mile south of Spring Run (Fig. 17); the Nealmont is about 50 feet thick in this area, and, if the clay is that of the upper Oak Hall, the member thins almost to extinction.

The course, impure Rodman member is of a facies that is persistent at the top of the formation. The lower limit is gradational and thus cannot be defined readily. The persistence of the Salona

[59] Craig, ftn. 52 (1941).

[60] Rosenkrans, p. 122 of ftn. 55 (1934).

FIG. 16.—Exposure east of bridge over Elk Creek one mile south of Millheim, East Penns Valley; Curtin (Valley View) limestone beneath hammer, disconformably overlain by Nealmont (Oak Hall) limestone.

FIG. 17.—Quarry one mile south of Spring Run, Path Valley; 20 feet of lower Benner (Snyder) limestone (*BS*) disconformably above Hatter limestone (*H*), and below Mercersburg (Nealmont equivalent) limestone (*N*), which has a thick metabentonite near the base.

o clay a foot or two above the top is suggestive of essential conformity between the Nealmont and Salona formations. However, there is distinct angular unconformity and basal Salona overlap locally, as in the quarry on the hillside a mile south of Antes Gap (Fig. 18), where there are coarse beds far below the top of the formation. The lithology of the Rodman indicates a shallowing of

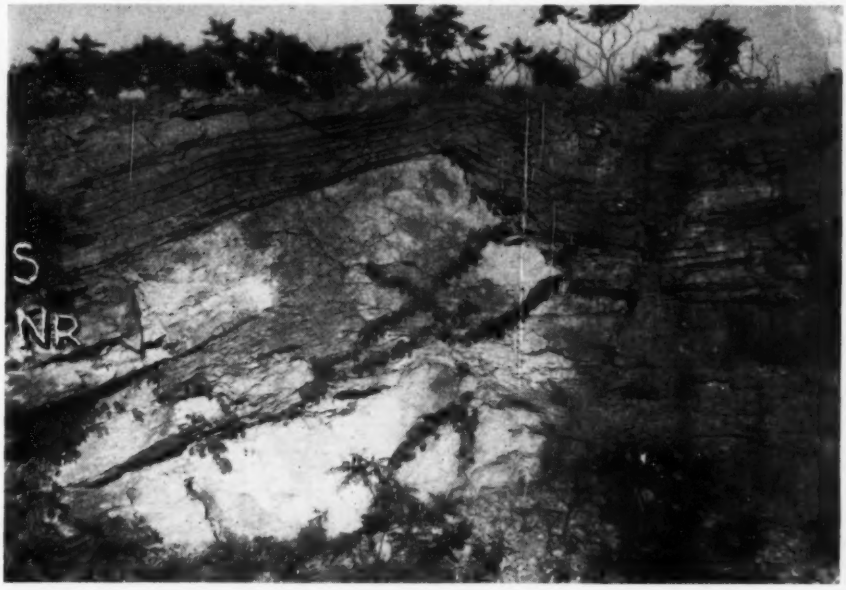

FIG. 18.—Well-bedded Salona limestone (*S*) disconformably overlying more massive Nealmont (Rodman) limestone (*NR*) in small quarry within road fork one mile southeast of Antes Gap, Nippenose Valley.

water such as would accompany marine offlap beyond the area. And in some places the basal Salona has lensing calcarenite lying on the undulating upper surface of the Nealmont, as in the quarry at Salona.

FAUNA

The Nealmont formation has a large fauna (Table 8). Though much of the formation is relatively barren of fossils, they are abundant in several facies. The basal beds of varying stratigraphic level are commonly of calcite sandstone or calcarenite in which *Columnaria halli* Nicholson is frequent; coquinas with *Strophomena* sp. often succeed. Calcarenite reaches the greatest thickness in channels in the Bellefonte region, containing corallites to 12 inches in diameter, brachiopods, trilobites, and other forms in abundance. The lower part of the Centre Hall member is of thin-bedded limestone with argillaceous partings; fossils are abundant on the bedding surfaces. Local calcarenite lenses higher in the member contain forms similar to those in the Bellefonte channels, though the latter are somewhat older (cf. 1*a* and 2*a*, Table 8). The Rodman member, dark, impure limestone, frequently is rich in bryozoans. Heavy ledges of rather dense limestone that

TABLE 8*

FAUNULES FROM THE NEALMONT FORMATION

	Localities															
	1a	1b	2a	2b	3	4	5	6a	6b	7a	7b	8	9	10	11	12
Nidulites sp.					×			×								
Columnaria halli Nicholson			×							z			×			
Lambeophyllum sp. cf. *L. apertum* (Billings)					×	×		×								
Lichenaria coboconkensis Okulitch		×														
Paleoalveolites sp. cf. *P. paquettensis* Okulitch	z															
Arthroclema sp.							×									
"*Chasmatopora*" (*Subretopora*) *reticulata* (Ulrich)		×														
"*Chasmatopora*" (*Subretopora*) *sublaxa* (Ulrich)		×											×	×		
Eridotrypa sp.												×	×			
Escharopora subrecta Ulrich							×				×	×	×		×	
Pachydictya occidentalis Ulrich													×			
Rhinidictya sp.					×	×	×	×			×	×	×		×	
Stictoporella sp.								×								
Ancistorhyncha sp.			×				×		×							
Camarotoechia (?) sp.			×													
Doleroides pervetus (Conrad)				×	×	×	×	×		×	×			×	×	
Glassia (?) sp.	×															
Glyptorthis sp. cf. *G. bellarugosa* (Conrad)		×						×		×		×	×			
Hesperorthis tricenaria (Conrad)				×	×	×	×	×	×	×	×			×	×	
Leptaena (?) sp. cf. *L. charlottae* Winchell and Schuchert	a	×	×										×			
Leptaena (?) sp.			×													
Öpikina inquassa (Sardeson)				×				×			×					
Öpikina minnesotensis (Winchell)	×					×	×				×		×	×		
Öpikina wagneri (Okulitch)					×	×		×			×				×	
Parastrophina hemiplicata (Hall)					×											
Porambonites sp.		×														
Rhynchotrema sp.	c	×										×				
Sowerbyella punctistriata (Mather)		×		×	×			×	×		×				×	
Strophomena sp. cf. *S. filitexta* (Hall)		×		×			×	×		×	×		×	×	×	
Strophomena sp.						×					×	×		×		
Valcourea sp. cf. *V. loricula* (Hall)							×				×				×	
Zygospira recurvirostris (Hall)		×	×							×		×		×	×	
Ambonychia (?) sp.																×
Metaconularia sp. cf. *M. ulrichi* (Foerste)	×															
Archinacella (?) sp.			×													
Cyclonema hallianum (Salter)	×															
Ecculiomphalus sp.	×		×													
Hormotoma canadensis Ulrich and Scofield									×							
Liospira americana (Conrad)					×	×		×			×					
Lophospira bicincta (Hall)					×				×		×					
Maclurites logani Salter				×	×	×	×	×	×	×		×				
Phragmolites sp.											×					
Subulites sp.						×				×						
Temnodiscus disculus (Billings)								×		×						
Trochonema sp.																
Diestoceras (?) sp.									×							
Geisonoceras (?) sp.			×													

TABLE 8—*Continued*

	Localities														
	1*a*	1*b*	2*a*	2*b*	3	4	5	6*a*	6*b*	7*a*	7*b*	8	9	10	11	12
Gonioceras sp. aff. *G. kayi* Foerste								×							×	
Loganoceras (?) sp.								×								
Paquettoceras allumettensis Foerste									×							
Tripteroceras sp. aff. *T. planoconvexum* (Hall)									×							
Acrolichas sp. cf. *A. cucculus* (Meek and Worthen)	×		×													
Basilicus barrandei Raymond not (Hall)												×				
Bumastus milleri (Billings)	c		c													
Calliops sp.	×							×								
Ceraurus sp. cf. *C. dentatus* Raymond and Barton	×										×		×	×		
Encrinurus sp.			×		×									×		
Illaenus americanus (Conrad)	f		c		×	×		×								
Isotelus sp.								×			×			×		
Thaleops ovatus Conrad	c		c										×	×		×
Aechmina (?) sp.					×											
Eurychilina subradiata Ulrich	×															
Hallatia (?) sp.		×														
Leperditia fabulites Conrad			c	×	×		×	×								
Macronotella sp. aff. *M. millepunctata* Kay										×						

* a, abundant; c, common; f, frequent; ×, present; "z," see locality. Localities: 1, Antes Gap, Nippenose Valley: 1*a*, Centre Hall member, single bed in bluff below Highway 45 east of limekiln; "z," small quarry south of highway ½ mile east; 1*b*, Rodman member, along roadside to north of bluff; 2, Bellefonte: 2*a*, 30-foot zone of calcarenite in channel in west end of Quarry 15½, probably upper Oak Hall member; 2*b*, Centre Hall member, shaly limestone, principally from Quarry 35 immediately above post-Valentine disconformity and corresponding beds in Quarry 15½; 3, Oak Hall: Centre Hall member at base in Oak Hall Quarry; 4, Centre Hall: Centre Hall member in quarry north of railroad station (Fig. 12); 5, Spring Mills: Centre Hall member near base, cut on Highway 45 west of bridge; 6, Highway 322, 1 mile west of Tusseyville (see Table 7): 6*a*, Centre Hall member above basal part; 6*b*, basal Centre Hall member, above metabentonite *Na*; 7, Naginey: 7*a*, Centre Hall member in quarry south of plant, "z," basal Oak hall member; 7*b*, basal Centre Hall member along tracks just north of plant; 8, Stover: Centre Hall member, stripped surface above north quarry; 9, Rodman station, exposure by Pennsylvania Railroad just northwest of Hatter Creek bridge, north of Roaring Springs: probably basal Centre Hall member; 10, ¾ mile south of Waterside: Centre Hall member in New Enterprise Quarry; 11, Blacklog: Oak Hall and Centre Hall members in north end of Grove (Binkley and Ober) Quarry; 12, 1 mile west of Rainsburg, small quarry west of Cover Creek: beds at base of Nealmont, overlying Stover limestone.

form most of the Oak Hall member, and interbeds in the Centre Hall member, are relatively unfossiliferous; specimens of *Maclurites* and *Gonioceras* are frequent, and occasional bedding planes have brachiopods and bryozoans.

CLASSIFICATION

The assemblage of fossils found in the Nealmont, if collected in New York or Ontario, could come only from the Rockland and Kirkfield formations. Inasmuch as other evidence corroborates this homotaxiality, the Nealmont is classified as lower Trenton. The fauna differs from that of the latter more in the absence of some of the common forms, and the association of species that are in separate units in the north, than in the presence of genera foreign to that area. Of the common genera in the Nealmont, *Doleroides*, *Glyptorthis*, *Gonioceras*, and *Thaleops* reach the upper limit of their range in the Rockland, and *Öpikina* and *Columnaria halli* Nicholson are rare above; *Hesperorthis* and *Maclurites logani* Salter are practically limited to the Rockland and Kirkfield, and *Parastrophina* and *Sowerbyella* first appear in them. The absence of species of *Dinorthis*, *Dalmanella*, and *Rafinesquina* in Pennsylvania is in marked contrast to their abundance in the north; also missing are *Triplesia cuspidata* (Hall) and *Recepta-*

culites occidentalis Salter, common in many areas of the Rockland, and *Platystrophia trentonensis* McEwan, a frequent Kirkfield species. In Pennsylvania, *Nidulites*, *Porambonites*, *Valcourea*, and *Amphilichas* are relatively rare genera in the Nealmont, though the first is common in the equivalent Mercersburg in the southeastern belts; a species of brachiopod listed as "*Leptaena*(?) aff. *L. charlottae* Winchell and Schuchert" is locally abundant, whereas only a single specimen has been found in the Ontario Rockland. The genus *Porambonites* previously has not been reported from North America, though it is common in the Baltic European Ordovician.

The Nealmont formation lies between a great regional unconformity and the Salona limestone that is correlated with confidence with the Shoreham and Denmark formations, a relationship similar to that of the Rockland and Kirkfield. The correlation of the members of the Nealmont with the northern formations is not so firmly established. The base of the Centre Hall contains at Tusseyville several of the cephalopods found in the upper Rockland at Paquette Rapids, Quebec, as well as *Maclurites logani*, described from that locality.[61] In a similar horizon at Oak Hall, *Parastrophina hemiplicata* (Hall) is frequent; the species is common in the Kirkfield in northwestern New York and has been found in the uppermost Rockland. The heavy-ledged character of the Oak Hall, more thin-bedded and argillaceous nature of the Centre Hall, and coarser texture of the Rodman approximate the facies of the Rockland, lower and upper Kirkfield of southeastern Ontario. Metabentonites give some further suggestions.

[61] Kay, "Ottawa-Bonnechere Graben and Lake Ontario Homocline," *Bull. Geol. Soc. Amer.*, Vol. LIII (1942), p. 598.

The two thick metabentonitic clays defining the upper 20 feet of the Oak Hall member in western Penns Valley are the only ones definitely placed in the Nealmont of Pennsylvania. The Rockland formation has a distinct metabentonite, the Hounsfield, near the base of the lower, Selby, member in northwestern New York.[62] The Kirkfield has a relatively thick and persistent clay near the base along West Canada Creek[63] in an area where the unit is thinning by overlap; the stratigraphic position should be about the middle of the formation, where it has maximum thickness. Thus, there are two widely separated metabentonites in the formations with which the Nealmont would seem to correlate. About 100 feet of Rockland and lower Kirkfield limestones separate their horizons in northwestern New York. Inasmuch as the fauna of the basal Centre Hall, succeeding the pair in Pennsylvania, is most similar to that of the top of the Rockland and base of the Kirkfield, it seems most probable that the known Kirkfield metabentonite is one of the two in the upper Oak Hall, preferably the upper.

CORRELATION

The Nealmont is in the stratigraphic position of the Mercersburg limestone of the Cumberland Valley. The former thins by overlap to the Path Valley. The latter thickens beyond until its thickness, 200 feet in the Chambersburg belt,[64] exceeds the maximum of the Nealmont; the manner of increase is not suggested.

Correlation with Pendleton County, West Virginia, and the western counties

[62] Kay, "Stratigraphy of the Trenton Group," *Bull. Geol. Soc. Amer.*, Vol. XLVIII (1937), p. 253.

[63] Kay, "Mohawkian Series on West Canada Creek, New York," *Amer. Jour. Sci.*, Vol. CCXLI (1943), p. 605.

[64] Craig, ftn. 52 (1941).

of Virginia clarifies the relations of some of the persistent units of the southern Appalachians. At Harpers Gap, West Virginia, 200 feet of shaly limestone lie between the Benner limestone and the base of the Salona. There is a distinct metabentonite about 30 feet from the base, overlying shaly limestone containing *Sowerbyella*, *Hesperorthis*, and *Doleroides*. The relations are much as in the Blacklog Valley, and the metabentonite may be *N2*, that at the top of the Oak Hall. North of Crabbottom, Highland County, Virginia, in similar stratigraphic position, are about 130 feet of similar shaly limestone with the same brachiopods, succeeded progressively by a thick clay, 70 feet of dense to coarser, white-weathering, relatively pure limestone, somewhat cherty, a second thick metabentonite, 15 feet of coarse, relatively pure limestone, and 60 feet of shaly limestone, yellow calcite-flecked lime mudstone, and sublithographic limestone bearing *Tetradium racemosum* Raymond—a total of about 275 feet. The lithology of the upper beds marks the introduction of facies that become prevalent in the upper Moccasin and Eggleston formations of more southerly areas. Inasmuch as there are two thick metabentonites in the middle of the section, it is probable that they correspond to the two defining the upper Oak Hall member of the Nealmont. If so, the Nealmont has diverged to twice the thickness in Pennsylvania, and the metabentonites have come to be nearly 70 feet apart, in contrast to a 20-foot interval to the north; the lower 200 feet in this section corresponds to the Oak Hall member, though the base may be older, and the upper 75 feet, to the Centre Hall and possibly the Rodman. There are two thick clays, V-3 and V-4, in rocks of similar lithology in the Eggleston formation of southwestern Virginia.[65] They have been correlated with two in the Tyrone limestone of central Kentucky,[66] where the upper conformably underlies the Curdsville limestone. The Curdsville long has been correlated with the Kirkfield limestone of Ontario,[67] on faunal grounds; the same conclusion is reached on stratigraphic evidence by way of central Pennsylvania, West Virginia, and Virginia, for the upper Tyrone would be equivalent to the upper Oak Hall limestone, correlated in turn with the lower Kirkfield.

SALONA LIMESTONE

DEFINITION AND DESCRIPTION

The Salona limestone[68] (village, Clinton County) comprises about 175 feet of dark argillaceous limestone and calcareous shale in the type section, which has been described by Whitcomb.[69] The base lies about 2 feet below metabentonite *O*;[70] the top contrasts with the Coburn in that the latter contains coarse-textured, somewhat coquinal limestone interbeds. The Salona contains several metabentonites, first recognized by C. A. Bonine and A. P.

[65] Rosenkrans, "Stratigraphy of Ordovician Bentonite Beds in Southwestern Virginia," *Va. Geol. Surv. Bull. 46–I* (1936), p. 104.

[66] G. G. Huffman, "Middle Ordovician Correlations from Lee County, Virginia, to Central Kentucky" (abstr.), *Bull. Geol. Soc. Amer.*, Vol. LIII (1942), pp. 1830–31.

[67] Frank Springer, "On a Trenton Echinoderm Fauna at Kirkfield, Ontario," *Geol. Surv., Canada, Mem. 15* (1911); A. F. Foerste, "The Mohawkian (Middle Ordovician) Strata Northeast of Manitoulin Island," *Geol. Surv., Canada, Guidebook 5* (1913), pp. 85–87.

[68] Field, p. 420 of ftn. 53 (1919).

[69] Lawrence Whitcomb, "Correlation of Ordovician Limestone at Salona, Clinton County, Pennsylvania," *Pa. Geol. Surv. Bull. G5* (4th ser., 1932).

[70] Rosenkrans, p. 115 of ftn. 55 (1934).

Honess,[71] that bear numbered designations[72] from the basal (*o*) upward; their correlation[73] within the region is well established, and an exceptional number of synchronous horizons demonstrate the continuity and essential constancy of the formation. The present study adds little to the knowledge of the formation the junction of Highway 45 and the Oriole side road in Nippenose Valley (Fig. 18).

The paired metabentonites *1* and *2* are unusally distinctive horizons of reference. Higher, between metabentonites *4* and *6*, the trilobite ***Brongniartella trentonensis*** (Collie) is constant and fre-

TABLE 9*

SEQUENCE OF METABENTONITES IN THE SALONA LIMESTONE

	1. Salona			2. Jacksonville			3. Bellefonte			4. Union Furnace			5. Blacklog			6. Willow Hill		
	Ft.	In.	Ft.	Ft.	In.	Ft.	Ft.	In.	Ft.	Ft.	In.	Ft.	Ft.	In.	Ft.	Ft.	In.	Ft.
Clay *7*	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	2	62
Interval	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	8	.....	.....
Clay *6*	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	8	202	.....	10	164	.....	6	53
Interval	B	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	54B	.....	.....	28B	.....	.....
Clay *5*	.....	1	121	.....	.....	.....	.....	6	98	.....	.....	.....	.....	10	109	.....	8	24
Interval	30B	.....	.....	B	.....	.....	30	.....	.....	109B	.....	.....	35B	.....	.....	6B	.....	.....
Clay *4*	.....	3	91	.....	10	79	.....	6	68	.....	11	92	.....	18	72	.....	3	17
Interval	28	.....	.....	34	.....	.....	30	.....	.....	43	.....	.....	26	.....	.....	7	.....	.....
Clay *3*	.....	3	63	.....	12	44	.....	3	38	.....	3	49	.....	12	45	.....	4	10
Interval	36	.....	.....	19	.....	.....	20	.....	.....	24	.....	.....	22	.....	.....	4	.....	.....
Clay *2*	.....	6	26	.....	8	25	.....	6	17	.....	16	13	.....	17	22	.....	6	6
Interval	2	.....	.....	2	.....	.....	2	.....	.....	2	.....	.....	.....	.....	.....	.....	.....	.....
Clay *1*	.....	2	24	.....	2	23	.....	2	15	.....	2	11	.....	.....	.....	.....	.....	.....
Interval	24	.....	.....	23	.....	.....	15	.....	.....	11	.....	.....	22	.....	.....	6	.....	.....
Clay *o*	.....	2	0	.....	2	0	.....	1	0	.....	1	0	.....	4	0	.....	3	0
Below *o*	2	.....	.....	2	.....	.....	2	.....	.....	1	.....	.....	.....	.....	.....	.....	.....	.....

* Totals in right-hand columns are thicknesses t *c* metabentonite *o*.

Localities: 1, below *1* from quarry, succeeding after Whitcomb; 2, lane west of Whiterock Quarry north of Jacksonville; 3, Bell Mine, American Lime and Stone Co.; 4, Pemberton Quarry, American Lime and Stone Co.; 5, composite, from lane north of St. Mary's Church and bluff along Shade Creek north of Binkley and Ober Quarry (Grove Quarry); 6, north side Pennsylvania Turnpike east of Highway 75 overpass, near Willow Hill. B, *Brongniartella* present.

along the Nittany Valley and southwestward; a single new exposure by the quarry north of Jacksonville shows the beds to metabentonite *4* to be comparable to those at Salona and Bellefonte (Table 9). The formation lies with essential conformity on the Rodman member of the Nealmont but is locally disconformable, as in the quarry south of

[71] "Bentonite in Pennsylvania," *Pa. Acad. Sci.*, Vol. III (1929), pp. 18–25.

[72] Rosenkrans, ftn. 55 (1934).

[73] Whitcomb, "Correlation by Ordovician Bentonite," *Jour. Geol.*, Vol. XL (1932), pp. 522–34.

quent. Along the Nittany Valley, between Salona and Union Furnace, the intervals between the successive clays are fairly constant and composed of fine-textured black limestone and platy shale.

Significant sections have been discovered in Blacklog Valley and farther southeast in Path Valley. The Salona in the former area is quite as in Centre County (Table 9), but in the few miles to Dry Run and Willow Hill in Path Valley it converges rapidly and becomes more shaly. The interval between meta-

bentonites *o* and *4*, the base of the *Brongniartella* zone, is 91, 79, 68, and 92 feet at Salona, Jacksonville, Bellefonte, and Union Furnace in Nittany Valley; 72 feet in Blacklog Valley, it diminishes to 17 feet in the section along the Turnpike at Willow Hill, becoming principally calcareous shale (Fig. 14). Between the last two sections the *Brongniartella* zone thins from 92 to 36 feet. Thicknesses of the clays are exceptionally great in Blacklog Valley. This seems not a result of folding, for the beds are on the northwest limbs of anticlines in all sections except that at Willow Hill and, with that exception, have dips of 60° or more; and there is variation in the relative thicknesses in sections along Nittany Valley. Clay *5* has not been recognized at Union Furnace, even though the beds are excellently exposed.

FAUNA

The fauna of the Salona formation in the type section has been exhaustively studied by Whitcomb, who published a summary.[74] Several faunules from the lower beds of the formation are listed in Table 10. Much of the dense, black limestone and dark shale is relatively barren, though some forms can be collected in nearly any exposure. *Brongniartella trentonensis* (Collie),[75] an interesting and stratigraphically useful fossil, has been found only between metabentonites *4* and *6* in the Salona formation.

CLASSIFICATION

The Salona formation is correlated with the Shoreham and Denmark formations of the type region of the Trenton group in New York. *Cryptolithus tessellatus* Green appears first in the basal Salona, particularly beneath metabentonite *1;* it is abundant in the Shoreham limestone in New York. A little higher in the Salona, *Geisonoceras tenuistriatum* (Hall) and *Sinuites cancellatus* Hall become common and *Trocholites ammonius* Emmons uncommon; these are abundant in the 5-foot *Trocholites* subzone in the base of the Poland member, 10 feet above the base of the Denmark formation in West Canada Creek Valley, New York;[76] *Diplograptus amplexicaulis* (Hall) is characteristic of the Poland and reported from above metabentonite *2* in the Salona.[77] A thin metabentonite that persists just above the *Trocholites* subzone in New York (Table 11, col. 3) may be clay *2* of Pennsylvania; higher are at least two clays present in Sherman Fall at Trenton Falls,[78] and a third parting 15 feet higher at the contact of the Poland and Russia members of the Denmark; a 5-inch clay is present 65 feet above the base of the Russia near Middleville. If these clays correspond to *3* to *6* in the Salona, the horizon of *5* correlates with the base of the Russia member of the Denmark limestone in New York. In any case, faunal similarity and sequence and frequence of metabentonites support the classification of the Salona below metabentonite *1* as Shoreham and that above as Denmark.

The basal Salona limestone differs from the Shoreham in having very few coquinal interbeds. The higher Salona is lithologically like the Denmark of West Canada Creek, and each changes to black shale southeastward; but the Denmark diverges in passing into the

[74] Whitcomb, ftn. 68 (1932).

[75] Whitcomb, "New Information on *Homalonotus trentonensis*," *Bull. Geol. Soc. Amer.*, Vol. XLI (1930), pp. 341–50.

[76] Kay, ftn. 62 (1943).

[77] Whitcomb, p. 1 of ftn. 68 (1932).

[78] Kay, "Distribution of Ordovician Altered Volcanic Materials and Related Clays," *Bull. Geol. Soc. Amer.*, Vol. XLVI (1935), Pl. 20.

Canajoharie black shale at the Adirondack axis, whereas the Salona above clay *1* converges in passing into the Martinsburg shale. The Shoreham limestone is continuous, though not constant, across the axis, and the basal Salona beds such as adjoin clays *1* and *2* in the type Salona persist in the Path Valley in and above the *Sinuites* zone, 6 feet of black, petroliferous, crystalline limestone at Willow Hill, having a metabentonite, probably clay *2*, in the middle.

TABLE 10*

FAUNULES FROM LOWER PART OF SALONA LIMESTONE

	Localities				
	1	2a	2b	2c	3
Echinosphaerites sp.	.....	.....	u	.....	c
"*Chasmatopora*" (*Subretopora*) sp. aff. "*C.*" *reticulata* (Ulrich)	.....	u	.....	.....	.....
Prasopora sp. cf. *P. orientalis* Ulrich	.....	.....	.....	.....	u
Rhinidictya trentonensis Ulrich	.....	f	.....	.....	.....
Dalmanella sp.	c	a	c	.....	c
Leptaena sp. aff. *L. rhomboidalis* (Wilckens)	a	c	f	f	u
Leptelloidea pisum (Ruedemann)	a	.....	u	.....	.....
Oxoplecia sp. cf. *O. simulatrix* (Bassler)	.....	c	c	.....	u
Salonia magniplicata Cooper and Whitcomb	T	.....	.....	.....	r
Sowerbyella sp.	.....	.....	.....	.....	c
Strophomena sp.	.....	.....	.....	.....	f
Rafinesquina sp.	.....	.....	.....	a	.....
Sinuites cancellatus (Hall)	.....	.....	.....	u	.....
Geisonoceras tenuistriatum (Hall)	.....	.....	.....	a	.....
Trocholites ammonius Conrad	.....	.....	.....	f	.....
Bumastus sp.	.....	u	.....	.....	.....
Calymene senaria (Hall)	r	.....	.....	.....	.....
Cryptolithus tesselatus Green	.....	f	.....	.....	.....
Cryptolithus sp. cf. *C. concavus* Whittington	a	c	.....	.....	.....
Cryptolithus sp.	.....	.....	.....	c	.....
Echarpes sp.	.....	r	.....	.....	.....
Illaenus sp.	.....	.....	.....	.....	f
Isotelus gigas (Dekay)	.....	.....	.....	c	.....
Tetralichas trentonensis (Conrad)	r	.....	.....	.....	.....

*a, abundant; c, common; f, frequent; u, uncommon; r, rare; T, type from 12 feet from base of Salona in railroad cut to the west. Localities: 1, quarry at Salona: light-gray, "ashy" limestone at base of Salona: 2, Whiterock Quarries, Pleasant Gap: *2a*, dense, dark limestone near base of Salona on shelf at top of quarry nearest kilns; *2b*, loose on stripped surface southwest of large quarry west of kilns, mixed with Nealmont (Rodman) fossils; *2c*, black, argillaceous limestone below metabentonite *2*, above collection *2a*; 3, quarry north of Bethlehem Steel Company office, Naginey: dark, impure, medium- to coarse-textured limestone in basal Salona at top of quarry.

passes into the Greencastle limestone in the Champlain belt.

CORRELATION

The basal Salona is represented in the southeast by the Greencastle limestone of the Chambersburg region. Cephalopod The underlying *Christiania* (*Bimuria*) zone, the Greencastle, contains a species of *Leptaena* that is present in the lowest Salona and has not been found in other horizons. The beds above the *Sinuites* zone are dark, somewhat calcareous shale that might be classed either as

shaly Salona or as limy Martinsburg; that the metabentonites they contain (Table 9) include clays *3* to *6* is evidenced by the presence of *Brongniartella* above and below the third, No. *5*. There is another, higher clay.

Southwestward at Harpers Gap, Pendleton County, West Virginia, the Salona can be recognized confidently; a pair of clays 40 feet from the base, like *1* and *2*, lie on *Leptaena*-bearing limestone (Table 11). Succeeding limestones, dark and dense, like the Salona, have several clays that must correspond to those in Pennsylvania. A pygidium of *Brongniartella* came from loose blocks along a lane by the road corner 2 miles south of Key, clay *4* lying on a cherty surface along the near-by roadside, stratigraphically lower.

Rosenkrans[79] suggested the correlation of the pair of metabentonites at the base of the Martinsburg shale south of Strasburg, in the Shenandoah Valley, Virginia, with the *1* and *2* pair in the Salona. The writer[80] correlated the lower Martinsburg with the Sherman Fall formation of northwestern New York, later[81] divided into the Shoreham and Denmark limestones. The basal Martinsburg clays overlie the *Christiania* zone that corresponds to most of the Greencastle limestone that has been correlated with the part of the Salona underlying clays *1* and *2* in central Pennsylvania;

TABLE 11*

COMPARISON OF METABENTONITES IN SALONA EQUIVALENTS

	1. Composite Section, Salona Limestone; Central Pennsylvania			2. Salona; Harpers Gap, West Virginia			3. Denmark; West Canada Creek, N.Y.			4. Martinsburg Shale; Strasburg, Va.		
			To Clay 2			To Clay 2			To Clay 2			To Clay 2
Clay 7		2″	143′		4″	174′						
Interval	8′			11′								
Clay 6		10	135		6	163		5″C	120′			
Interval	54 B						65′C					
Clay 5		6	81					1 D	54		6″	62′
Interval	30 B			102 B			15			14′		
Clay 4		6	51		12	60		1	39		4	48
Interval	30			49			9			32		
Clay 3		3	20		16	10		1	30		12	15
Interval	20			10			30			14		
Clay 2		6	0		12	0		1	0		6	0
Interval	2			2			5 E		5 E	1		
Clay 1		1	− 2		4	− 2					3	1 F
Interval	15			37 A		39 A				27 G		−28 G
Clay 0		1	− 17									
Interval	2 A		− 19 A									

* 1. See Table 9; section at Bellefonte to clay *5*, Blacklog Valley to clay *6*, Willow Hill to clay *7*. B, *Brongniartella;* A, base of Salona formation.

2. Along road 1 mile southeast of Harpers Gap, Pendleton County, West Virginia; B, *Brongniartella;* A, base of Salona formation.

3. Composite along West Canada Creek, central New York; C, base Canajoharie shale facies, Russia member; D, contact, Russia and Poland members; E, base of Poland member, contact with Rathbun member.

4. Along Highway 11, south of Tumbling Run, south of Strasburg, Virginia; F, base of Martinsburg shale; G, base *Christiania* (*Bimuria*) zone or Greencastle limestone.

[79] Rosenkrans, "Bentonite in Northern Virginia," *Wash. Acad. Sci.*, Vol. XXIII (1933), pp. 413–19.

[80] Kay, pp. 234–35 of ftn. 77 (1935).

[81] Kay, pp. 264–69 of ftn. 61 (1937).

hence subsequent work verified the correlation of Rosenkrans.

In summary, the Salona limestone extends southwest to Pendleton County, West Virginia. The lower part, below clays *1* and *2*, is approximately equivalent to the Shoreham limestone of New York, the Greencastle limestone of the Chambersburg region, southern Pennsylvania, and the *Christiania* zone of the Shenandoah Valley, Virginia. Most of the Salona is equivalent to the Denmark limestone of the typical Trenton of New York and the lower part of the Martinsburg shale of southern Pennsylvania and the continuing belt of the Shenandoah Valley.

COBURN LIMESTONE

The Coburn limestone[82] (village, East Penns Valley, Centre County) comprises the somewhat coquinal limestone succeeding the Salona and underlying the black shale of the Antes formation. The section at the type locality has not been described, and only that at Salona[83] seems to have been adequately studied, the thickness being 300 feet, the fauna summarized very briefly. Raymond[84] correlated the Coburn with the Cobourg limestone of Ontario. Inasmuch as the Salona is correlated with the subjacent Denmark, and the Antes shale with the overlying Holland Patent shale of New York, the Coburn must be approximately equivalent to the Cobourg. In New York and Ontario the Lower Cobourg is more coquinal and calcarenitic than the Denmark and is disconformably succeeded near Utica, New York, by black shales of the Holland Patent, reflecting relative shallowing and subsequent deepening of water, such as is also evidenced in the Salona, Coburn, and Antes of Pennsylvania.

ANTES SHALE

The Antes shale (new; Antes Creek, Clinton County) comprises about 400 feet of dark, brownish-weathering shale lying between the Coburn limestone and silty and arenaceous Reedsville shale along Antes Creek above Antes Gap, Clinton County. *Dicranograptus nicholsoni* (Hall) is abundant in the formation near the top in a small pit along Highway 44 at the bridge over the creek; *Triarthrus eatoni* Hall is common in underlying shales and is also found in the exposures along the Milesburg road (Highway 220) near the road junction north of Bellefonte. The Antes shale has been included in the Reedsville shale in the reports and on maps of the region. The lithology resembles that of the Upper Utica (Holland Patent) of central New York, while the succeeding Reedsville is like the corresponding Frankfort and equivalent Whetstone Gulf shales of New York. *Dicranograptus nicholsoni* is common in the Holland Patent, though also in the older Canajoharie (Denmark equivalent) shale;[85] inasmuch as the Salona limestone is of the age of the Denmark, the *Dicranograptus* zone in the Antes shale seems to correspond to that in the Holland Patent, with which it is thus correlated on lithologic and faunal bases.

PART III. CONCLUSIONS

The Middle Ordovician of central Pennsylvania comprises about 1,500 feet of limestone and shale representing the Chazyan and Mohawkian series. The rocks are classified into formations and

[82] Field, p. 404 of ftn. 53 (1919).

[83] Whitcomb, p. 1 of ftn. 68 (1932).

[84] P. E. Raymond, "Correlation of the Ordovician Strata of the Baltic Basin," *Mus. Comp. Zoöl. Harvard College, Bull.*, Vol. LVI (1916), Pl. 8.

[85] Rudolf Ruedemann, "The Utica and Lorraine Formations of New York, Part I: Stratigraphy," *N.Y. State Mus. Bull. 258* (1925).

members, and their correlations are discussed. The study reveals the larger aspects of the stratigraphy of most of the formations, but much is to be learned of intraformational relations; whereas conclusions have been reached, many problems remain to be solved.

The Loysburg and Hatter formations are classed as Chazyan; more precise correlation is not attempted. The relationship of the Loysburg to the older Canadian series has not been determined satisfactorily; the upper members are extensive and quite constant. The succeeding Hatter formation overlaps the Loysburg southeastward and partially corresponds to the Shippensburg limestone of Cumberland Valley; the stratigraphy of the lowest member, the Eyer, needs clarification, and the manner of the disappearance of the members in the northeast is not determined; fossils suggest equivalence with formations to the southwest, but evidence for correlation with the divisions of the standard Chazyan is insufficient.

The Black River group of the Mohawkian has the Benner and Curtin limestone formations. They thicken northwestward from extinction in western Cumberland Valley; the increase is somewhat by basal overlap but preponderantly by offlap and truncation. The Benner formation has maximum thickness in a northeastward-trending belt in the western part of the outcrop area, considered to be a southwestward extension of the Rideauan trough of New York in which the equivalent Pamelia limestone is thickest. The Curtin is limited to the northwest, thickening as it disappears from view along the northern Allegheny Front; isopachs trend more easterly than those of the Benner. The upper, Valentine, limestone member is the principal source of chemical lime, the stratigraphy having important bearing on the distribution and reserve of this important economic product. The thickening of the Black River group resembles that in the eastern part of the Allegheny belt in New York but contrasts in that older beds are more extensive southeastward in Pennsylvania, the younger in New York.

The Trenton group of the Mohawkian series is represented by the Nealmont, Salona, and Coburn limestones and the Antes shale. The lower Trenton, Nealmont, lies with great regional unconformity and local marked disconformity on older beds; overlap is principally responsible for its thinning from the maximum in the northwest-trending belt approximately in the position of that of the Benner limestone. The middle Trenton Salona formation, of dense, argillaceous limestone, is quite constant in character and thickness in most of the area; the lowest beds lie disconformably on the Nealmont and extend southwestward beyond Path Valley into the Greencastle limestone of Cumberland Valley; the succeeding and largest part of the formation converges rapidly as it approaches Path Valley and passes into dark Martinsburg shale on the southeast. The Coburn limestone and Antes black shale of the upper Trenton seem equivalent to the Cobourg and Holland Patent (Upper Utica) beds in New York; their stratigraphy in Pennsylvania is not sufficiently known.

Earlier studies have recognized the abundance and stratigraphic utility of metabentonites in the section. Several are present in the Benner, Curtin, Nealmont, and Salona formations; their presence has permitted many precise correlations that enhance stratigraphic studies.

The Middle Ordovician rocks of

central Pennsylvania lie along the eastern margin of the Allegheny stratigraphic belt, west of the Adirondack belt of oscillation and lesser depression that borders the miogeosynclinal Champlain belt; the Adirondack axis is along Path Valley. The rocks thicken northwestward and were laid entirely west of the principal geosynclines of Middle Ordovician time. Their broader regional relations will become more evident as the stratigraphy of the sediments in the eastern part of the Allegheny belt in West Virginia and Virginia is presented.

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POTHOLES, PITS, AND PANS: SUBAERIAL AND MARINE

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ABSTRACT

Potholes produced by fluviatile abrasion, subaerial solution pits, both subaerial and marine flat-bottomed pans produced by possibly several processes, and marine potholes—all occur in Hawaii. Each is found in a certain typical combination of variety of rock and physical and chemical condition. In some places two or more of these sorts of depression are found together or there is indication of transition from one to another. In their character and their occurrence these potholes, pits, and pans illustrate the principle that a locally dominant process may, with change of either place or time, lose its dominance by transition from a favorable to an unfavorable type of rock, by weakening of a part or all of the physicochemical factors under which it operates, by being overmatched by some other locally dominant process, or, more commonly, by some combination of these occurrences. This is true despite the fact that under present knowledge we cannot always accurately or even approximately predict the result of a new combination of factors and rocks.

INTRODUCTION

By prevailing textbook interpretation, potholes are due to the abrasive action of running or falling water with rock fragments as tools. In elementary textbooks, potholes are offered as one of the typical results of river abrasion. Although the occurrence of marine potholes has been noted,[1] they are mentioned in few, if any, textbooks; and presence of potholes is commonly regarded as proof of fluviatile or fluvio-glacial action. The writer just cited, in his classification and description of potholes, includes various pits and other depressions chiefly due to solution, but it does not appear that this usage has been followed by most critical students. In fact, such pits and other details of differential weathering are not well covered in textbooks, and most students are poorly prepared for the variety of localized depressions that are not abrasion potholes. Unfortunately, such pits may be tempting and misleading examples if used by the inexperienced teacher in a region where genuine potholes are rare. The present writer believes that the term "pothole" should be restricted to products dominantly of abrasion, that the occasional local occurrence of marine-abrasion potholes should be recognized, and that various pits, pans, and other depressions due to solution or other kinds of nonmechanical wastage should be described and more adequately treated in textbooks. The purpose of the present paper is to deal with some aspects of these features of contrasted origin and to consider both fluviatile and marine forms as found particularly in Hawaii.

[1] E. D. Elston, "Potholes, Their Variety, Origin, and Significance," *Sci. Monthly*, Vol. V (1916), pp. 554–67.

FLUVIATILE POTHOLES

For a land of torrential stream flow, steep gradients, and widespread outcrops of rock, potholes cannot be considered to be abundant or striking in Hawaii. They are found sparingly in channels in all the local rocks, including basalt of various formations, tuff of such cones as Diamond Head, claylike basaltic residuum, calcareous reef rock, and calcareous sandstone. In many of the major streams of Hawaii there are waterfalls with heights from a few feet to one hundred feet or more. At the base of these falls are plunge pools, which are usually in part cut or broken in rock. Relatively

very few of these pools are smooth enough and symmetrical enough to be called "potholes." On the faces of falls in some channels, small crevices due to irregularity of rock structure may favor the formation of groups of chink-faceted pebbles. These are due to agitation by water insufficient in amount or energy to develop a pothole or dislodge them al-

FIG. 1.—Fall with successive parabolic grooves cut in basalt and with enlarged plunge pool and downstream boulder accumulation. The Sacred Fall in Punaluu Stream, windward Oahu.

together.[2] Most of the falls do not have a vertical drop, owing to the lack of a sufficiently strong ledge at the lip, but the face is often roughly parabolic in adjustment to the horizontal and vertical components of the dominant flood velocities. In some striking instances the form of the face and of the sides of a narrow gorge is traced downward in a striking parabolic carving of the wall rock, to end in a plunge pool of somewhat greater area than the discharge section at the lip (Fig. 1). Failure of development of typical potholes in such places is probably due to variability of stream flow, deficiency of well-sorted, hard tools, prevailing conditions of clogging in the pools, relative effectiveness of chemical weathering, and variability, thinness, and jointing of lava-flow bedrock.

The making of striking, symmetrical potholes is favored by the thicker lava flows of certain later series of trachytes which form the upper parts of some of the domes of Hawaii, such as Haleakala of East Maui, or the ultrabasic Honolulu series of southeast Oahu. In some of these, quite impressive series of potholes have been developed locally, aided by the thickness due to emplacement in valley bottoms and to the juvenile, maladjusted character of stream channels in such valleys (Fig. 2).

In contrast to the widespread, often differentially weathered, lava flows, the dense masses of dikes or sills are occasionally the sites of potholes. Despite the comparative weakness of tuff and of weathered residuum, these rocks are sufficiently compact and so uniformly massive that they favor the temporary development of good potholes in channels of rills and ephemeral streams. The reef and detrital varieties of limestone are chiefly found at very limited elevations above the sea, but potholes are occasionally developed in them by small streams.

MARINE POTHOLES

Marine potholes are found in places where bedrock is exposed in the zone of wave action or at points where returning spray and surf water are the agents of erosion. The roundest abraded boulder

[2] Chester K. Wentworth, "Chink-faceted Pebbles: Fluviatile versus Marine," *Jour. Geol.*, Vol. LI (1943), pp. 353–58.

the writer recalls ever seeing was forming, and being formed in, a nearly perfect hemispherical pot in basalt on the coast of Molokai, the boulder and pot differing very little in curvature.[3] Deepening and smoothing of such depressions depends on the development of an initial hollow sufficiently deep to retain rock detritus suitable for abrasion tools. In the pitted zone back of the solution benches previously described,[4] pits of various sizes are formed by solution; and many of these develop as widening, flat-bottomed pans which eventually merge to form the solution bench. In suitable places these pits in reef limestone serve as lodgment sites for basaltic pebbles and cobbles, or the harder fraction of coral gravel, and may develop into rounded and deepened true potholes through action of both onshore waves and returning salt water (Fig. 3). This may take place at 5 or 10 feet above sea-level, inland from the solution bench; or such pits may be carried below the level of this shelf. Such abrasion potholes may also be started on the bench at points where detritus accumulates. It is usual for the well-developed, dominant solution bench along a limestone coast to give way in a few yards to increasingly numerous potholes and eventual dominance of an abrasion ramp as the mouth of a small stream is approached, owing to the delivery of cobbles and boulders to the shore zone by the stream.

FIG. 2.—Typical, small potholes cut in the Tantalus member of the Honolulu basalt series, in the channel of Pauoa Stream.

The reef and detrital-limestone shores of Oahu are especially suited to marine-pothole development, since, for the most

[3] C. K. Wentworth and H. S. Ladd, "Pacific Island Sediments," *Univ. Iowa, Studies in Nat. Hist.*, Vol. XIII, No. 2 (1931), p. 19, Fig. 8.

[4] Wentworth, *Jour. Geomorph.*, Vol. II (1939), pp. 3–25.

part, the limestone formations reach but a few feet above sea-level and their pitted upper surfaces are within the range of storm action. Lava formations on an uncliffed coast may have a similar relationship. Along coastal cliffs cut in basalt or in tuff, potholes may be developed at points where streams bring in detritus, monly deepened and smoothed by pothole action where wave action is favorable and where detritus is available. Such potholes may be seen in the Hanauma Bay and Koko Head area and elsewhere on tuff shores. Or, on basalt shores where differential weathering or concentrated spilling of return water produces

FIG. 3.—A shallow marine pothole cut in the surface of the solution bench near Makua, Oahu. The rock is reef limestone; other incipient potholes showing abrasion are also shown, though algae are still growing on the general surface.

where the floors of small valleys are cut down to the wave zone, or where the cliff is fringed by an emerged bench. Near the mouths of small streams occur potholes formed in part by stream water and in part by wave action.

On the water-leveled bench elsewhere described,[5] as with the solution bench, pits and hollows formed by the process responsible for the bench are not uncom- an initial hollow, this may be deepened to a typical pothole if tools are available. Such potholes have been observed at Makapuu Head and elsewhere. Marine potholes of various sorts on a bench of complex origin, in both limestone and tuff, may be seen on the bench of the northwest shore of Ulupau Head.

SOLUTION PITS IN INLAND SITES

The surfaces of basalt outcrops in Hawaii most commonly have an irregularity due to differential weathering of

[5] Wentworth, "Marine Bench-forming Processes: Water Level Weathering," *Jour. Geomorph.*, Vol. I (1938), pp. 6–32.

the lava flows and the accentuation of variations in vesicularity, flow lines, or jointing. In some places the wasting of the surface may take on the form of a characteristic fluting, on sloping surfaces, as described by H. S. Palmer,[6] or of one or many pits, either round or flat-bottomed. The best development of such pits or flutings appears to be in the more massive rocks, either of thick flows, intrusive bodies, or the thick, valley-filling flows of the Honolulu ultrabasic series. Well-marked pits were observed on the tops of the intrusive "buds" in the Waialaenui area and elsewhere[7] and in occasional thick masses of the Koolau series, but especially on blocks of the Kaau flow in Palolo Valley, the Nuuanu flows, and the Kalihi flows—all of the ultrabasic series. Two sites are typical: the tops and sloping sides of isolated blocks, commonly where they stand under trees, and the slopes of flows where they are exposed and kept somewhat bare in and near stream channels (Fig. 4).

In some instances the individual pits occur in places where drip from trees appears largely responsible for the wastage. In other places the pits are numerous, roughly equispaced, and subequal in size, with cuspate ridges and points between them (Fig. 5). Probably the subequal size and regular arrangement are due to some rhythmic and repeating process of the sort found not infrequently in nature, but it is not easy to deduce what the controlling factor may be. Where the pits are not too near stream channels, the texture of the rock surface is often rough and may show protruding, hard crystal aggregates or otherwise indicate clear marks of chemical corrosion. On the other hand, the pits sometimes seen on rock surfaces in stream channels, though indicating differential solution, are developed on surfaces that are subject to sufficient abrasive action to keep the surface smooth.

In the limited areas where reef or detrital limestone is exposed inland from the shore zone, the rock is commonly very rugged and pitted and locally shows the deeply pitted and systematically cuspate surface so common in many limestone areas of the world.[8] The texture and pattern of such surfaces is commonly controlled by details of detrital or organic structure and in Hawaii generally lacks the large scale of development found in more massive reef limestones on some other Pacific islands or in continental limestone masses.

Most of the masses of palagonite tuff, such as Diamond Head and similar craters, have, in part, barren surfaces subject to weathering and erosion, including that of the wind, which produce a rugged, scraggly, pitted, and often undercut or perforated surface, in which both major and minor structures of the tuff are strikingly accentuated. That the tuff is susceptible to attack by solution is certain; but the pits and depressions in it are, for the most part, varied and manifold in origin and with their rough surfaces are less attractive examples of the work of a specific agent. The surface of the tuff is often especially pitted in retiform or areolar pattern on the upper brows of marine cliffs 30–100 feet above the sea, where the effect of spray is probably important; and such pits may furnish the initial stage of some of the higher

[6] "Lapies in Hawaiian Basalts," *Geog. Rev.*, Vol. XVII (1927), pp. 627–31.

[7] C. K. Wentworth and A. E. Jones, "Intrusive Rocks of the Leeward Slope of the Koolau Range, Oahu," *Jour. Geol.*, Vol. XLVIII (1940), pp. 986–90.

[8] Pits of the kind discussed in this section are described and illustrated by Elston as a variety of pothole, but to the present writer this extension of usage seems objectionable. (See pp. 563–64 of ftn. 2.)

FIG. 4.—Solution pits in a large block of Nuuanu basalt, Nuuanu Valley

FIG. 5.—Solution pits at the top and on the sides of a large block of Koolau basalt, north of Waipahu. Back of the pitted surface is a slightly depressed surface which appears to be the floor of a water-leveled pan, now rendered inoperative through the cutting-away of the sides.

examples of water-level weathering, to be mentioned below.

The pits described here intergrade, of course, into all manner of depressions on rock outcrops at all altitudes. These are abundant in size and variety, owing to thinness and textual variations of the explosive formations. Any further consideration of these would take us beyond the scope of this paper.

FIG. 6.—Solution pits in limestone of the pitted zone inland from the solution bench near Kawela Bay, Oahu. A glimpse of the solution bench appears in the upper left corner.

MARINE SOLUTION PITS

It seems fitting to include the pits in limestone antecedent to the solution bench as marine, since the initial baring of the surface, as well as the limiting of their downward development, is accomplished by the sea. As described elsewhere, these pits are believed to be due to solvent action by fresh rain or land water in the zone a few feet above tide-level, where the soil cover is removed from the margin of the emerged reef rock by wave action.[9] These pits are one to several feet in diameter and are slowly deepened, while probably being widened at a more rapid rate (Fig. 6). The depth to which they are finally corroded is apparently set by the level, a few inches to 2 or 3 feet above mean tide, below which the solvent effect of standing fresh water is limited by the frequent invasion of sea water. The pits widen and become merged at this level to form a continuous bench facing the sea and with the zone of growing pits at its back, on the landward side. A few of the component pits which have been overdeepened in the making of the bench are progressively filled by

[9] Wentworth, ftn. 4.

accumulation of detritus bound and invested by growing algal veneer unless their situation and presence of suitable tool detritus favors their continuance and growth as marine potholes.[10]

Pre-existing benches or gently sloping surfaces on tuff are subject to water-leveling, which in its initial stages takes the form of a marked widening at the water-level of any depression which holds water. Deepening is relatively very slow as a rule, unless some structural irregularity or accident causes pitting. The most marked water-level action is usually slightly inland from the immediate water line and separated from it by a pitted rampart, which is often marked by smaller, fairly deep, but flat-bottomed pits.[11] The surfaces of the pits and pans due to water-leveling are rough, both because of the nature of the process and because the tuff, even under the most favorable condition, does not acquire a very smooth surface. The dominance of the widening tendency is shown not only by the shallowness of the pans and the striking way in which they truncate dipping beds but also by the undercut form of the margins of the water-leveled areas.

INLAND PANS

Pans may be defined as flat-bottomed, water-holding depressions developed on rock surfaces by some process which favors widening at a somewhat controlled level and is relatively inactive in deepening. It is not to be expected that all pans are due to precisely the same causes, any more than that the causes of pitting are everywhere identical. Kirk Bryan has described various forms of water-holding rock depressions in relation to rock structure.[12] The present writer and many others have observed the striking pans up to several feet in diameter which occur on the surfaces of the outcrops of coarse granite in the Graniteville area of Missouri. Whether these are due to wetting and drying processes similar to those postulated for the coastal water-leveling of Hawaii or are due to freezing effects in the coarse, granular rock or some other cause cannot be definitely stated.

None of these pans is quite so surprising as are some found on surfaces of massive basalt in Hawaii. Such pans occur in places associated with the round-bottomed pits. A notable locality is in the channel of Kalihi Stream on ultrabasic basalt of the Kalihi flow. Here, in the stream channel on surfaces that are dry most of the time but are submerged during freshets, are some very distinctly flat-bottomed depressions from 6 inches to 2 feet in diameter. They are slightly undercut around part of the margin, usually with a well-marked outlet or low spot in the rim, and are nowhere more than $\frac{1}{2}$ inch deep below the outlet (Fig. 7). Some appear to be the leveled bottoms of potholes which have lost a side; others occur on large boulders or flow masses where the cause of the initial depression is not apparent (Fig. 8). All are relatively smooth and are in positions where they may be subjected to general abrasion or moderate pothole action, so far as debris is retained. Potholes are also common in this stream channel, and ordinary solution pits are typical of this basalt on slopes near the channel or remote from it.

MARINE PANS

The best of these are the water-leveled areas a few inches to many feet across which have already been alluded to at

[10] Tide pools noted by Henkel on Vancouver Island appear from the descriptions to be due more to solution than to abrasion (Isabel Henkel; *Postelsia, The Yearbook of the Minnesota Seaside Station* [1906], pp. 277, 304).

[11] Wentworth, ftn. 5.

[12] "Origin of Rock Tanks and Charcos," *Amer. Jour. Sci.*, Vol. L (4th ser., 1920), pp. 188–206.

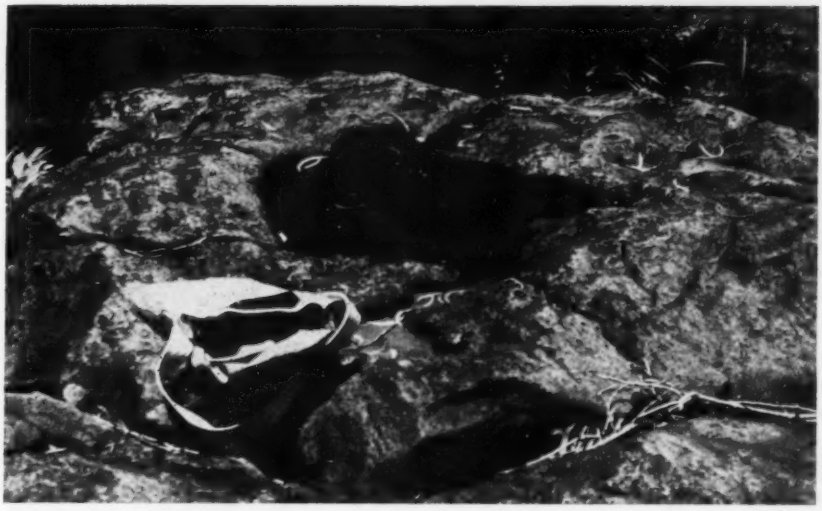

FIG. 7.—Flat-bottomed pan cut in Kalihi basalt near the channel of Kalihi Stream. The contained water is nowhere over ½ inch deep, and the outlet is seen cutting across the near margin.

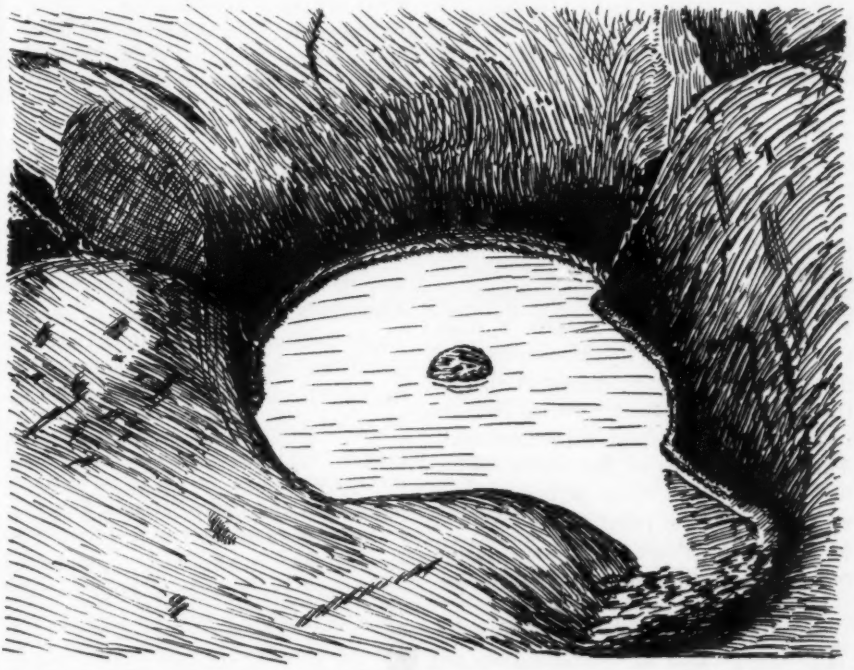

FIG. 8.—Flat-bottomed pit which was perhaps initially a pothole. Cut in Kalihi basalt in the channel of Kalihi Stream. The small pebble was purposely placed near the center to show the shallowness of the retained water, fixed by the outlet at the near margin. Drawn from a photograph.

various points in this paper and have been described in detail elsewhere. The evidence of the hybrid bench at Ulupau Head suggests that, above sea-level, action of sea water is more effective on tuff than on reef rock but that, once a level is reached where the surface is kept more continuously wet and where marine organisms grow, the destructive action is most rapid on the reef rock.[13]

A similar but less marked tendency toward leveling is shown by the pits in limestone in the pitted zone inland from the solution bench. As stated elsewhere, normal pits or flat pans may, by the agency of detritus or other favorable circumstances, become deepened or modified in form by potholing.

COMBINED POTHOLES AND PANS

A particularly striking combination of potholes and pans was recently found on Kawaikoi Stream on Kauai. It is quite likely that other such examples occur in the channels of other streams of Kauai or elsewhere in Hawaii, but this is the most impressive yet recorded by the writer. Kawaikoi Stream is one of the headwater branches of the Waimea River drainage system, the latter being the most complex and mature in pattern of any in the Hawaiian Islands. Kawaikoi Stream is formed by the convergence of several small branches which rise on the surface of the western end of the surface of Alakai Swamp at about 4,000 feet. The swamp is one of the characteristic high-level, sloping bogs of Hawaii and reaches its highest point at the east end in Mount Waialeale, with an elevation of 5,080 feet and a mean annual rainfall of 460 inches. The southwestern margin of the swamp is frayed by the head branches of Waimea and other stream systems, forming a belt of sloping upland with a local relief of 300–500 feet. This belt stands between the swamp, with its local relief of not over 50–100 feet, and the heads of the canyons of Waimea, Olokele, and other streams, 2,000 or more feet in depth.

The course of Kawaikoi Stream across this belt is about 2 miles long, and the channel is marked in places by numerous large boulders, 5–20 feet in diameter. The locality at which the potholes here described were observed is a few rods downstream from the main cart trail crossing at the intake of a ditch and tunnel line leading to the Kekaha plantation system. The weir-type dam diverting water into the ditch has been constructed by consolidating and bridging across the mass of large boulders in the channel at this point. The channel is one hundred or more feet wide and at the margins is seen to be cut 20 or 30 feet below the surface of the weathered residuum. The bank shows a transition downward to great kernels of only slightly altered basalt, shaped by spheroidal weathering, and no doubt the source of the great numbers of large boulders in the channel. Those remaining represent the lag after quantities of slightly smaller boulders have been carried downstream and perhaps over the fall into the main, lower canyon. In this vicinity very cursory observations indicate that the local terrane consists of very thick basaltic flows.

Notwithstanding the evidence that stream flow is at times competent to move and rearrange these large boulders, their local origin justifies caution in interpreting the volume and velocity of discharge from their size and shape and suggests the possibility that the mass of

[13] C. K. Wentworth and J. E. Hoffmeister, "Geology of Ulupau Head, Oahu," *Bull. Geol. Soc. Amer.*, Vol. L (1939), pp. 1557–59; also "Hybrid Shore Bench at Ulupau Head, Oahu," *Jour. Geomorph.*, Vol. III (1940), pp. 57–58.

larger boulders now in the channel may have been stable for a long period.

Potholes and pans seen here were wholly formed on boulders; none were observed on bedrock, though they could probably be found at favorable points. However, it appears that the development of potholes is here caused particularly by the local declivities and turbulence produced by the tumbled mass of great boulders at this point. A very tortuous irregularity of flow and marked variations with changes of discharge and stream stage are evident to anyone examining the site with this factor in mind. Many boulders are so lodged as to offer a clear drop of 10 or 15 feet on one or more sides; and many openings of large size, but highly variable in capacity and configuration, are found among the boulders (Fig. 9).

FIG. 9.—Potholes cut in boulders of Kawaikoi Stream, Kauai

Some of the individual potholes are cut in several juxtaposed boulders, suggesting either an intact matrix or a very persistent local turbulence. Certain boulders are bored by several potholes, so as to cut away the larger part of their volume (Fig. 10). Without extensive observation at various stages of flow it is impossible to deduce the exact flow behavior under which the various potholes have been formed. There seems no justification for assuming that pothole abrasion has taken place under conditions that now no longer exist. Rather, it is thought that abrasion of the lower potholes is carried on much of the time and that with increasingly higher stages higher potholes are occasionally affected. It is pertinent that stage increases in feet are much greater, proportionate to discharge increases, in such a boulder fabric than they would be in a clear channel of such dimensions. It may be that ex-

FIG. 10.—Parts of three large boulders cut by potholes. The near half of the picture consists of the perforated and fantastically carved remnant shell of a single boulder.

FIG. 11.—A pan cut in the top of a boulder of Kawaikoi Stream. The hammer rests everywhere within a fraction of an inch of the flat bottom.

treme stages reach the higher potholes only at intervals of some scores of years.

Because of the dependence of pans on somewhat flat upper surfaces on which to develop, they are chiefly found on the tops of the higher boulders. They range from a few inches across to 2 or 3 feet in diameter and may be either nearly circular or somewhat elongate and irregular. The bottoms are flat but not smooth and are usually less than an inch deeper than the outlet, though the undercut margins may be up to 2 or 3 inches below the adjacent surface of the rock. As elsewhere, their surfaces are roughened by differential etching, as distinguished from the smoothly abraded surfaces of the fresher potholes (Fig. 11).

The initimate association of potholes due to abrasion and pans attributed to solution is still more striking where a pothole is developed in a pan, or at least where a pothole at its upper margin is fringed by a pan several times its own diameter. As suggested above, the writer does not consider that either process in its entirety antedates the other. It may be that the detritus lodged in a growing pan has, under favorable circumstances, performed the work of boring a pothole with dimensions determined by the prevailing hydraulic conditions (Fig. 12). It is not necessary to

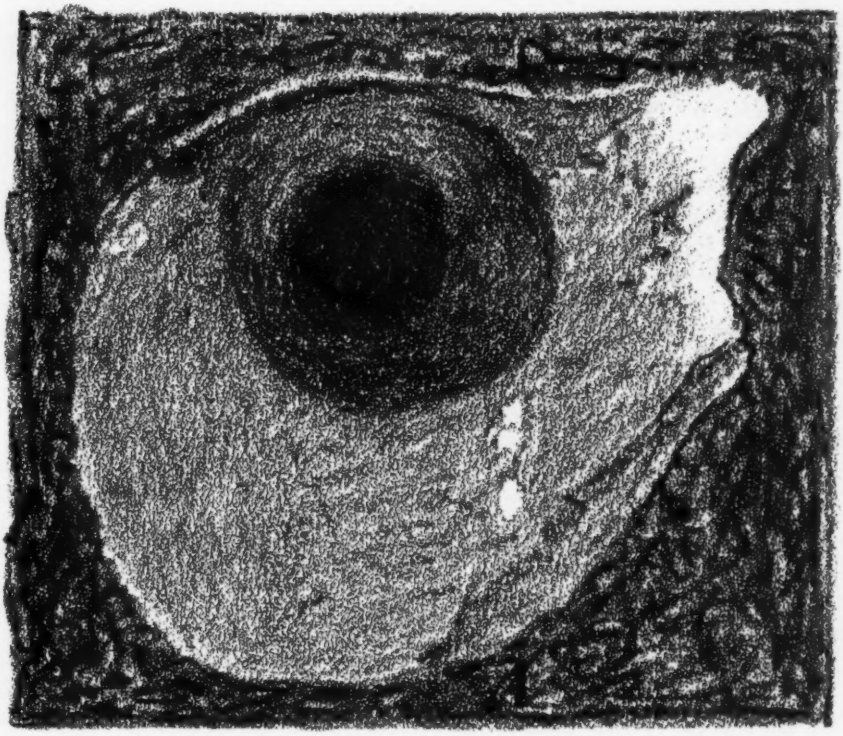

FIG. 12.—A combined pan and pothole, the former about 20 inches across. The pan is very shallow, and the pothole about 2 feet deep.

assume that the diameter of potholes is systematically less than that of pans; obviously, only those combinations so characterized have survived for consideration. It is perhaps also possible, though a little less plausible, that the upper margin of an existing pothole may have been widened by solution or other action fixed by the water-level into a pan. We do not actually know what part is taken in the water-level action by warming of the water of a shallow hollow, by restricted action of dissolved gases, or by alternation of wetting and drying at the water line. It is not clear, therefore, whether the greater depth of a part of the water, as in one of these combined depressions, and the greater volume present would be adverse to the physicochemical conditions which lead to formation of pans.

SUMMARY

The purpose of presenting these collected observations on potholes and pans is to emphasize that, whereas under optimum processes and on optimum rocks strikingly typical products, such as potholes, may be produced, the import of these processes and the special quality of these rocks go much further than this. The force and clarity of expression of a given process may fade through the replacement of the optimum rock by another, less favorable rock or by the overlapping or intermittent domination of another process. In almost all regions of sufficient size the reciprocal waxing and waning and alternate domination of mechanical weathering and chemical waste can be observed in some places, as a response to changing conditions of exposure, declivity, rock composition, and the like. A process may lose its prominence and its distinctive expression not through its own inherent weakening but only because its realm is overwhelmed by another, locally more powerful agency, such as the mechanical attack by the force of waves on an exposed coast. And yet, even on the surfaces of the wave-eroded coast there are new and subtle processes of more minute destruction or construction whose sites of operation are prepared by the action of waves. A product may be regarded as distinctively, or necessarily, marine or fluviatile but may prove only to have been conditioned by combinations in which the fluviatile or marine element was only one, and perhaps not strictly the essential, factor. These facts, encountered in our contact with a widening world, enjoin stricter and more fundamental observations and the realization that, before accurate historical interpretations can be made in various parts of the world, we require a far more critical understanding of geologic processes everywhere than we now possess.

SOME STRUCTURAL FEATURES OF OHIO

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ABSTRACT

The major structural features of Ohio are the Cincinnati arch, the Parkersburg-Lorain syncline, the Cambridge arch, and a few other related folds in the eastern portion of the state. The general alignment is north-south.

The faults in Ohio have small throw, and strikes which vary little east or west of north. They are chiefly normal and apparently related to the major warping.

The minor folds have considerable diversity of trend, but the axes of more than two-thirds of them fall within the quadrant, N. 0°–90° W., with the largest number approximately northwest-southeast. They show a shift in direction from almost north-south in northeastern Ohio to east-west in the southern portion of the state. A corresponding change is noted in the orientation of the jointing in the coal beds, although, in general, the joint sets are not parallel to the axes of the folds. Those in the coal are more regular than those in the other rocks. Apparently the forces which produced the folded Appalachians were mainly responsible for the structural features of Ohio.

CINCINNATI ARCH

Extending from northern Alabama through Nashville, Cincinnati, and Toledo into northern Canada, there is a belt of uplifting, approximately paralleling the western side of the Paleozoic Appalachian geosyncline. The most prominent features of this belt are the Nashville dome and the Cincinnati arch.

There is evidence that the Cincinnati arch was in existence in upper Cambrian time. Isabel B. Wasson's[1] cross section across northern Illinois to southern Ohio shows the Dresbach sandstone of upper Cambrian age laid down on the warped and truncated Eau Claire sandstone of the same epoch. Another section,[2] from central Indiana to northern Ohio, shows the Jordan, Mazomanie, and Dresbach formations tilted and truncated before the deposition of the lower Magnesian (Prairie du Chien) formation of early Ordovician age.

Late Ordovician beds are exposed around Cincinnati, but certain members of the stratigraphic column, from the base of the Niagara dolomite to the top of the Delaware limestone, known as the "Big Lime" by the drillers, apparently passed with diminished thickness over the Cincinnati arch. Some geologists favor the view that Mississippian and lower Pennsylvanian rocks once covered the arch, connecting the Appalachian and Interior coal basins. From available data, the crystalline-rock surface, upon which the Paleozoic sediments rest, indicates a steep slope toward the Appalachian geosyncline. It appears that the pre-Cambrian crystalline complex formed a highland area in northwestern Ohio. Wasson[3] points out that a pre-Cambrian granite ridge follows the axis of the Cincinnati arch. This would separate the area into two basins, east and west, with different sedimentary histories, which appears to have been the condition, since the sediments of the two basins are different.

Charles W. Wilson[4] gives us the probable processes by which the Cincinnati

[1] "Sub-Trenton Formations in Ohio," *Jour. Geol.*, Vol. XL (1932), p. 476.

[2] *Ibid.*

[3] *Ibid.*, p. 687.

[4] "The Pre-Chattanooga Development of the Nashville Dome," *Jour. Geol.*, Vol. XLIII (1935), pp. 449–81.

arch was formed. He points out that the Nashville dome

> was developed synchronously with the mountain-building activity in Appalachia. When Appalachia was active, the dome was above sea-level and when inactive, the dome was covered by calcareous sediments.

He believes that

> the Nashville dome was uplifted essentially by vertical bulging caused by the stresses transmitted plastically in the deeper rocks of the crust. Uplift occurred many times, the axes of greatest uplift shifting east or west in accord with the intensity of the stresses transmitted westward from Appalachia.

In a later paper[5] he has extended the treatment to include the behavior of the Cincinnati uplift as a "complementary arch" in the late Paleozoic Appalachian orogeny. The reader is referred to Wilson's article for a very clear presentation of that concept.

An arm of the Cincinnati arch branches off in Kentucky, not far south of Cincinnati, and extends from southeast to northwest across Indiana, disappearing near Chicago. In western Ohio the arch is a broad, low structure, the formations dipping away from the axis into the Appalachian geosyncline to the east. There is a gentle dip northward along the crest.

MAJOR STRUCTURES IN EASTERN OHIO

The axes of the major structural features in eastern Ohio are plotted on the map (Fig. 1), from data obtained from the Ohio Geological Survey. Subsurface structure maps,[6] already published, show the attitude of the Trenton limestone, Clinton sandstone, and Berea sandstone. From west to east the major structures are the Rutland and Amesville terraces, the Parkersburg-Lorain syncline, and the Cambridge arch. The outstanding structural feature of the eastern half of Ohio is the Parkersburg-Lorain syncline, a deep trough which can be traced on surface beds from Parkersburg on the Ohio River northwestward to Lorain County on Lake Erie. To the east, the Cambridge arch more or less parallels the Parkersburg syncline and enters Ohio in eastern Washington County. It is a series of uplifts and continues north and west through Noble, Guernsey, Coshocton, and Holmes counties. The axes of the Parkersburg-Lorain syncline and Cambridge arch have a trend of about N. 10° W., which is approximately the same as the strike of the majority of faults in Ohio. East of the Cambridge arch the normal east dip of the formations is broken by minor structures, which have a northwest-southeast trend. The axes of the minor folds do not parallel the major structures, except in the northern part of the coal area. In southeastern Ohio the two trends are nearly at right angles to each other. The major structures are not parallel with the Appalachian folds nor are they in line with those of the Michigan Basin, unless the latter bend abruptly in the Lake Erie region to join the major structures in eastern Ohio. According to R. P. Grant,[7] the general trend of the folding in the Michigan Basin is approximately N. 45° W. These trends are not straight and uninterrupted.

MINOR FOLDS IN OHIO

The data for locating the minor anticlinal and synclinal structures were ob-

[5] Wilson, "Connection of the Nashville and Ozark Domes," *ibid.*, Vol. XLVII (1939), pp. 583–97.

[6] Wilber Stout and Others, "Natural Gas in Central and Eastern Ohio," *Amer. Assoc. Pet. Geol.* (1935), pp. 897–914.

[7] Petroleum geologist, Geological Survey Division, Dept. of Conservation, Lansing, Michigan, personal communication.

tained from structural maps filed in the office of the state geologist at Columbus, which have been brought up to date by geologists of the Survey. These maps were contoured on selected key horizons, this coal is quite uniform and abundant information on it is available. Table 1 shows the formations used as key horizons by the Ohio Survey.

On the map (Fig. 1), the crests of the

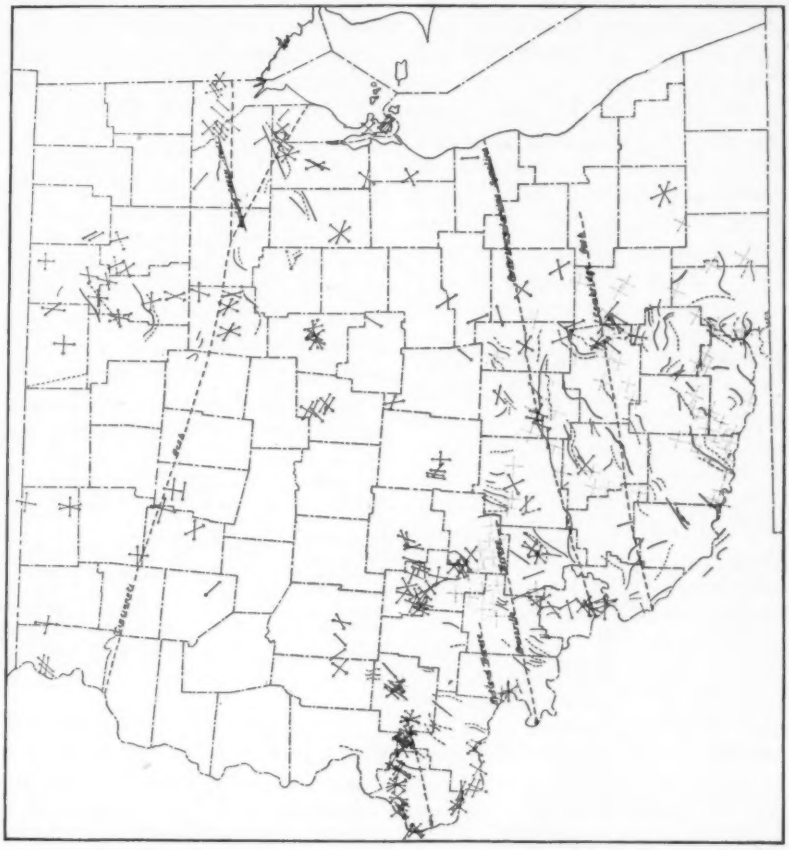

FIG. 1.—Map of Ohio showing structural features. The heavy broken lines indicate the major structures. The minor folds are indicated by broken lines representing the crests of the anticlines and solid lines for the crests of the synclines. The approximate position of the faults, with the exception of the Bowling Green Fault, is indicated by the letter F. The joints in the rock formations are indicated by solid straight lines tipped by barbs. The joints in the coal beds are straight, light dotted lines.

whose elevations have been obtained from well logs, mine records, or outcrops. The number of quadrangles involved totals 66. In 19 eastern quadrangles, the No. 8 coal is used as a key horizon, as anticlines are represented by broken lines and the axes of the synclines by solid lines. The number of anticlines and synclines on all the quadrangles is 97 and 95, respectively, making a total of 192.

TABLE 1

Quadrangle	Horizon
Waverly	No. 1 coal
Wellsville	No. 7 coal
Conesville	No. 6 coal
Coshocton	Putnam Hill limestone
Cumberland	No. 8 coal
Dover	No. 6 coal
Alger	Trenton limestone
Alliance	Berea
Antrim	No. 8 coal
Athalia	No. 8 coal
Cambridge	Cambridge limestone
Elmore	Trenton limestone
Columbiana	No. 7 coal
Clarington	No. 8 coal
Chesterhill	No. 8 coal
Carrollton	No. 7 coal
Caldwell	No. 8 coal
Cadiz	No. 8 coal
Brinkhaven	No. 4 coal
Bowling Green	Trenton limestone
Bidwell	No. 6 coal
Athens	No. 8 coal
St. Marys	No. 8 coal
Salineville	No. 7 coal
Scio	No. 8 coal
Sciotoville	Sciotoville clay
Steubenville	No. 8 coal
Tiffin	Trenton limestone
Uhrichsville	No. 6 coal
Zanesville	No. 6 coal
Zaleski	No. 4 coal
Woodsfield	No. 8 coal
Wilkesville	No. 4a coal (Clarion)
Arlington	Trenton limestone
Findlay	Trenton limestone
Flushing	No. 8 coal
Frazeysburg	Lower Mercer limestone
McConnelsville	No. 8 coal
Macksburg	No. 8 coal
Marietta	No. 8 coal
Millersburg	Putnam Hill limestone
Newcomerstown	Putnam Hill limestone
New Matamoras	No. 8 coal
Oak Hill	Van Port limestone
Point Pleasant	No. 8 coal
St. Clairsville	No. 8 coal
Guyandot	No. 8 coal
Ironton	No. 5 coal
Jackson	Clarion coal
Keno	No. 8 coal
Lisbon	No. 7 coal
Logan	Lower Mercer limestone

Table 2 indicates the strike of the folds.

These figures indicate that a large number of folds have a strike of N. 0°–90° W. The most common trend lies within N. 0°–45° W. The next most prevalent direction is N. 45°–90° W.

Some figures indicating the length of a number of the more important minor structures are shown in Table 3.

TABLE 2

Number	Strike	Number	Strike
51	N. 0°–90° E.	22	N. 0°–45° E.
130	N. 0 –90 W.	29	N. 45 –90 E.
3	N.–S.	74	N. 0 –45 W.
8	E.–W.	56	N. 45 –90 W.

TABLE 3

Quadrangle	Length in Miles	Strike of Axis
Elmore	Anticline, 18	N. 26° W.
Elmore	Syncline, 15	N. 26 W.
Cambridge	Anticline, 19	N. 23 W.
Antrim	Syncline, 17	N. 30 W.
Coshocton	Syncline, 19	N. 5 E.
Coshocton	Anticline, 18	N. 5 W.
Conesville	Syncline, 18	N. 20 W.
Tiffin	Syncline, 14	N. 24 W.
St. Clairsville	Syncline, 19	N. 38 W.
Newcomerstown	Syncline, 21	N. 35 W.
Navarre	Syncline, 16	N. 50 W.
Lisbon	Syncline, 15	N. 16 W.

In northwestern Ohio the minor folds have a trend of N. 10°–35° W., their axes making an angle with the axis of the Cincinnati arch. In Columbiana and Carroll counties in northeastern Ohio the folds have a north-south direction to N. 20° W. Farther south in Harrison, Belmont, Tuscarawas, Holmes, and Guernsey counties, the general axial trend is about N. 40°–60° W. Still farther south in Muskingum, Morgan, and Athens counties, their direction is N. 50°–70° W. In Jackson, Gallia, Scioto, and Lawrence counties, the strike of the axes ranges from N. 55° W. to a nearly east-west direction. These trends show a decided

shift from an almost north-south direction in northeastern and northwestern Ohio to a nearly east-west trend in the southern portion of the state, although there are some folds which do not conform to the general trend.

FAULTS

With a few exceptions, the faults in Ohio are not of great throw, nor can they be traced any great distance. Only the Wood County fault, often referred to as the Bowling Green–Findlay fault, which has a length of at least 12 miles and an estimated throw of 200 feet, is plotted on the map (Fig. 1). The faults in Ohio have a general trend, approximately north-south, but ranging somewhat east or west of north. Many of small displacement have been observed by miners but have not been recorded. In the railroad cut near the steel bridge north of the village of Mineral City, located directly south of the city of Canton, in Tuscarawas County, there is a fault cutting beds of Pennsylvanian age. This fault has a vertical displacement of more than 15 feet and a dip of 45°–50° to the west, the downthrow being in the same direction and the strike about north-south. It cannot be traced on the surface, nor has the writer been successful in getting information concerning this break from coal miners and operators who have mined in this area for many years. A fault was reported by Clinton R. Stauffer[8] in Campbell's quarry, on the east side of the railroad track near Delaware, Ohio. It is described as having a throw of 8½ feet and a strike of N. 20° E., passing to the south into a distributive fault of greater complexity. According to Paul Shaffer,[9] it is a high-angle fault, dipping east at an angle of 58°. Faults of small displacement are reported in the Salineville area and at the McLain clay mine near Irondale. One, reported in the Kidd mine near Quincy Station on the Baltimore and Ohio Railroad, is considered the prolongation of a fault that was noted in Wheeling Creek mines in Pease Township. A normal fault, showing a throw of 7 feet and a north-south trend, was noted by a miner in a mine located between Wilkesville and Clarion. A reverse fault, having a strike of N. 5°–10° E. and a throw of 1½–2 feet, is reported by an engineer in the No. 8 seam of coal in the Hanna Georgetown No. 12 mine in Shortcreek Township, Harrison County. Stripping has uncovered about 150 feet of the fault. A few faults reported from the northeastern portion of Ohio have a northeast-southwest trend, parallel to the Appalachian structures.

The faults of the Bowling Green–Findlay area of northwestern Ohio are the largest in the state. Considerable faulting is found on the top of the Cincinnati arch in Hancock and Wood counties. In the latter the Cincinnati arch, having a trend of north-northeast, is crossed by the Wood County fault having a direction of N. 10° W. This is known as "the break" by the drillers. It is best known in central Wood County, west and southwest of Bowling Green, and can be traced to central Hancock County and northward through Lucas County to the Michigan state line. According to J. E. Carman and W. Stout,[10] in Wood and Hancock counties it is a fault zone or very steep monocline, dropping the Trenton oil horizon on the west, 100–200 feet, as evidenced by well records. Only in one short quarter-mile strip, on the floor of the Maumee Valley on the north line of

[8] "The Middle Devonian of Ohio," *Ohio State Geol. Surv., Bull. 10* (4th ser., 1909), p. 87.

[9] Geologist, Ranney Water Corporation, personal communication.

[10] "Relationship of Accumulation of Oil to Structure and Porosity in the Lima-Indiana Field," *Bull. Amer. Assoc. Pet. Geol.* (1934), pp. 521–29.

Wood County and in near-by quarries, is this fault known to outcrop. Here it is a crush zone, 10 feet wide, almost vertical, and striking N. 20° W. North of the Maumee River in Lucas County, the strike becomes nearly north-south, and the displacement is 200 feet for a distance of several miles. Farther north, across Lucas County into Michigan, the trace of the fault is located on the westward-dipping limb of the Cincinnati anticline; the dip is steepened, forming a narrow, westward-dipping monocline. From the evidence available, it appears that the Wood County fault plays out southward, passing into a number of parallel, steep flexures which have located oil and gas accumulations.

The only other prominent fault which has been identified from subsurface work is located about 5 miles from Carey. According to Ralph Koenig,[11] this fault trends northwest-southeast, with its northwest extension in the direction of the Wood County fault. It is possible that these faults may connect. It has been suggested that the earthquake[12] of March, 1937, centering at or near the town of Anna, may have been due to deep-seated faulting, the village being in line with the Wood County (Bowling Green–Findlay) fault. If extended, this faulted zone would reach the approximate position of the cryptovolcanic structure in southwestern Ohio near the point where Adams, Highland, and Pike counties meet.

Grant[13] points out that the "hinge lines" in Michigan, as mapped in *U.S. Geol. Surv. Monograph No. 53* by Leverett, just about parallel the trends of folding in the Michigan Basin. It is thus possible that movements along faults in northwestern Ohio may have occurred during the rise of the area toward isostatic equilibrium after depression by the ice sheets. In any case it appears that the majority of structural features in northwestern Ohio lie in a northwest-southeast direction, as do the trends of the structures of the Michigan Basin immediately to the northwest.

JOINTING IN THE COAL BEDS OF OHIO

Throughout most of the coal area in eastern Ohio, the joints in the coal beds show remarkable uniformity in trend[14] and usually occur in two sets, known as the face and the butt joints, which stand at right angles to each other. One set extends northeast-southwest and the other northwest-southeast. In southern Ohio, however, the orientation changes, one set trending a few degrees north of east or nearly east and west. The change in orientation of the joints in the coal beds appears to be arranged in an arc, the convex side to the west. This curve corresponds to the arc of folded Appalachians in the same latitude in Pennsylvania. While there is varied opinion as to the origin of the cleat in coal, it is difficult to explain the systematically changing orientation of the joints, the fact that in successive coal beds in the same area the cleat joints have approximately the same trend, and the parallelism with the folded Appalachians to the east in the same latitude unless one believes in the theory of tectonic origin. The joints were presumably formed by the deformation at the time the Appalachians were folded.

A study of the map reveals that the

[11] Geologist, Ohio Oil Company, Findlay, Ohio, personal communication.

[12] John T. Rouse and R. R. Priddy, "Recent Earthquakes in Western Ohio," *Ohio Jour. Sci.*, Vol. XXXVIII (1938), pp. 25–34.

[13] Personal communication.

[14] Karl Ver Steeg, "Jointing in the Coal Beds of Ohio," *Econ. Geol.*, Vol. XXXVII (1942), pp. 503–9.

shift in direction of the joints in the coal beds from northeastern to southern Ohio is accompanied by a similar change in direction of the axes of the minor synclines and anticlines. In the northern portion of the coal area the general trend of the anticlines and synclines usually bisects the angle between joint sets, although a number of the axes approach parallelism with the northeast-southwest set of joints. In Belmont County the axes of the folds are more nearly parallel with the northwest-southeast set of joints. In Muskingum, Perry, Athens, and Meigs counties the fold axes approach parallelism with the east-west set of joints. There are exceptions to these generalizations, for it is evident that the folding was quite feeble and very irregular.

JOINTING IN THE OTHER ROCK FORMATIONS

The observations on the trends of the joints in the sedimentary rock formations in Ohio were made by the author during the summers of 1940, 1941, and 1942. At each locality a number of observations was made, the plotted directions representing averages. In most cases two directions are prominent; at other points, three trends are conspicuous. In general, the joint sets are well defined and their directions easily determined. Most of the joints are vertical, or nearly so, and give no definite clue to the forces which produced them. The general directions of the joint sets in the noncoal formations are shown on the map (Fig. 1) and the graph (Fig. 2). The greatest numbers fall within the directions, N. 25°–80° W. and N. 25°–80° E. Table 4 indicates the percentage of joints lying within certain directions. The most common fracturing is thus in two directions at approximately right angles, northwest-southeast and northeast-southwest.

It was found difficult to distinguish between shear and tension joints. Whether a particular set of joints was formed by tension or by shear is none too clear. All we can be sure of is that these joint

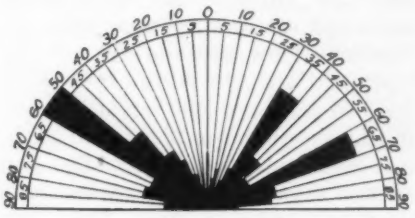

FIG. 2.—Graph showing relative number and direction of the joints in the rock formations. North at top.

TABLE 4

Percentage	Direction
42	N. 25°–80° E.
36	N. 25 –80 W.
22	N. 25 W.–N. 25 E.
29	N. 30–70 E.
28	N. 50–60 W.

systems were caused by regional stresses in brittle rocks under conditions in which lateral relief was easier than upward relief. Sets of nearly vertical joints may be formed by tensile stresses in gently folded sediments, showing a close relation to the folds. One set—the strike joints—parallels the general strike of the folds, and the other—the dip set—follows the direction of dip. The strike joints are caused by stretching over the crest of the fold; the other set results from stretching along the pitch of the fold.[15] It is probable that many joints in Ohio are of the tension type. On the other hand, observations in the field show that a great number of well-developed joint faces are not ragged and ir-

[15] Charles Nevin, *Principles of Structural Geology* (3d ed.), p. 140.

regular, like those one might expect in tension fractures, but cut across lithologic irregularities with smooth planes, such as are produced by shearing stresses.

In the southwestern part of Ohio, west and on the axis of the Cincinnati arch, and to a lesser degree farther north in the state, the joint sets trend nearly north-south and east-west, varying from the directions most common east of the Cincinnati arch. In northwestern Ohio two well-developed joint sets are present, trending northwest-southeast and northeast-southwest. The joints in this part of Ohio show up to good advantage in the great limestone quarries. This is true throughout the limestone area of western Ohio. Here the trends are easily determined; the smooth joint faces sometimes extend for great distances. In some cases only one set is strongly developed, whereas in others two or even three are well defined. In most cases the joints are vertical, or nearly so.

In northwestern Ohio the northwest-trending axes of the minor folds bisect the angle between the two joint sets. This is a common feature throughout the state. In the coal area the joint sets in the rock formations show a marked parallelism to those in the coal beds. The jointing in the coal is somewhat more irregular than in the other strata, although the differences are not great. Since the joints are probably of tectonic origin, one would expect the well-developed joints to cut through both the thin seams of coal and the other rock strata, above and below, with no great differences apparent.

The compiled data included in this paper are to be considered an extension of what is known structurally of western New York and Pennsylvania.

ACKNOWLEDGMENTS.—The writer expresses his appreciation to Wilber Stout, state geologist of Ohio, and the Ohio Geological Survey for the use of structural maps.

REVIEWS

Upper Cretaceous Floras of the Rocky Mountain Region; Part I: *Stratigraphy and Paleontology of the Fox Hills and Lower Medicine Bow Formations of Southwestern Wyoming and Northwestern Colorado;* Part II: *Flora of the Lance Formation at Its Type Locality, Niobrara County, Wyoming.* By ERLING DORF. (Carnegie Institution of Washington Publication 508.) Washington, D.C., 1938–42. Part I: Pp. 78; pls. 19; figs. 8; Part II: Pp. 81; pls. 17; figs. 3. Paper, $2.50; cloth, $3.00.

One of the notable debates in the history of American geology has been that concerning the proper placement of the boundary between the Cretaceous and the Tertiary in the interior of North America. A considerable group of geologists has participated, generally with vigor and sometimes with asperity. Between 1910 and 1925 there seemed no possibility of reconciling the opposing views, but since then, through the work of a new group of investigators, especially R. W. Brown and Erling Dorf, more accurate information has become available, and the debate has waned. Complete agreement is very near, though no one of the older views has been entirely supported. It is reassuring to note in retrospect how long-standing misconceptions and obsessions have been gradually cleared away and how each lot of new information has added its bit toward an acceptable settlement of the problem.

Three stratigraphic levels for the boundary were proposed, each supported by able students of the question: (1) between the Fox Hills sandstone and the overlying Lance formation; (2) between the Lance formation (or Laramie in some areas) and the various overlying units, Arapahoe, Dawson, or Fort Union formations; and (3) between the Fort Union formation and the Wasatch formation. The first and third are now considered untenable. The second, with modifications, is the accepted view, and the present publication by Dorf is powerful support.

Part I, issued in 1938, gives, in order, a discussion of the stratigraphic classification for the late Upper Cretaceous deposits of the Hanna Basin, Wyoming, and the Yampa Valley, Colorado, measured sections and records of the contained fauna and flora, a general discussion of the flora and its significance as to climatic conditions, a correlation with other floras, a summary of results, and finally a systematic section describing and illustrating sixty-four species of plants. It is concluded that the climate of Medicine Bow time was warm-temperate to subtropical and that the flora is most closely related to those of the lower part of the Lance formation of Montana (Hell Creek), the "Laramie" of Black Buttes, Wyoming, the lower part of the Denver and Dawson formations, and the Vermejo formation and lower part of the Raton formation of Colorado. The flora is distinct from those of the upper part of the Lance formation of Montana (Tullock) and the Dakotas (Ludlow) and of the Fort Union formation. Because the flora is found above the *Sphenodiscus* zone (Fox Hills) and in or below the *Triceratops* zone, it is of Cretaceous age.

Part II, issued in 1942, presents a history of geologic studies in the Lance Creek area, Wyoming, a description of the stratigraphic section with lists of the contained fossils, a discussion of the flora and its climatic significance, a correlation with other floras, a summary of results, and a systematic section describing and illustrating seventy species of plants. It is concluded that the name "Lancian" should be applied to the time unit represented by the Lance formation and that it is of latest Cretaceous age, equivalent to the following formations: Laramie, Arapahoe, and lower part of the Denver, lower part of the Dawson, upper part of the Vermejo, lower part of the Raton of Colorado; "Laramie" of southwestern Wyoming, Colgate and Hell Creek of Montana and the Dakotas, Whitemud, and lower part of Ravenscrag of Canada. The Almond and Ericson formations of Wyoming, the Mesaverde formation and lower part of the Vermejo of Colorado, and the Fruitland formation of Colorado are pre-Lancian. The typical Fort Union formation and the Tullock, Ludlow, and Cannonball formations are Tertiary.

In the systematic sections of the two parts many changes in classification of species are

proposed and a relatively small number of new species is described. Dorf indicates that, of 57 definitely identified Lance species, 23 range from older beds to the top of the Lance and stop there, 29 are restricted to the Lance, 4 appear in the Lance and pass into the overlying Paleocene, and 4 range from below to above the Lance. The flora is thus very well characterized and supports the evidence of the invertebrates and vertebrates that the Lance and its equivalents are Cretaceous. The older thesis that the flora is intimately related to the flora of the Paleocene is shown to be untrue and the result in part of inaccurate identifications, in part of careless collecting.

The paper is well written and well illustrated and constitutes a pleasing as well as a useful contribution.

JOHN B. REESIDE, JR.

"Research on Early Man in Burma, with Supplementary Reports upon the Pleistocene Vertebrates and Mollusks of the Region by Edwin H. Colbert and J. Bequaert and Pleistocene Geology and Early Man in Java by Hellmut de Terra." By HELLMUT DE TERRA and HALLAM L. MOVIUS, JR. (*Amer. Phil. Soc. Trans.*, Vol. XXXII, Part III [1943].) Pp. 265–464; pls. 35; figs. 106.

The history of Pleistocene man in southeastern Asia and the main outlines of the Pleistocene geology of this area are set forth in this large and handsome report by De Terra and Movius. The pioneer work of the Cainozoic Laboratory of China, the bold exploratory work of De Terra in northwestern India, and the painstaking recent labors of von Koenigswald in Java have been brought into a coherent and orderly system by these new studies in Burma. The expedition was made in the winter of 1937–38 and financed by the American Philosophical Society, the Carnegie Institution, and Harvard University. The geologist, De Terra, and the archeologist, Movius, explored Upper Burma and the Shan States. For five months they had the help of Père Teilhard de Chardin and on their excursion to Java the leadership of G. H. R. von Koenigswald.

Upper Burma is a basin lying between the Shan Uplands on the east and the Arakan Mountains on the west. The climate is dry, as 90 per cent of the mean rainfall of 20–30 inches falls in the summer months. The periodic (monsoonal) rainfall and high temperatures in summer contrast with cool winters marked by occasional showers. The sparse vegetation facilitates geologic and archeologic field work.

The basin of Upper Burma is underlain by a great thickness of alluvial beds, the Irrawadian, folded and tilted by faulting. These are comparable to the Siwalik beds of northwestern India but have a more limited range in age. The lowest fossiliferous zones are Pliocene, and, separated by an unconformity, the higher zones contain a vertebrate fauna of Villafranchian age. One of the most important results of the expedition is the confirmation of this dating by newly collected fossils, identified by Colbert. Evidence of the angular unconformity between the Lower Irrawadian and the Upper or Pleistocene Irrawadian is a vital achievement. Thus the pre-Pleistocene and the post-Early Pleistocene movements of the Himalayas both previously proved in northwestern India have been demonstrated for this area. De Terra holds that these movements and the resulting unconformities are time-markers for the whole of southeastern Asia.

The remainder of Pleistocene time is represented by terraces and terrace deposits. The interpretation of these phenomena and their correlation with the glacial chronology are accomplished largely by means of a theory of soil formation. The ingenious use of soil phenomena furnishes a pattern for the study of Pleistocene deposits in all nonglaciated areas. Under the present climate, the soils of the arid basin of Upper Burma are pedocals with a yellow-brown subsoil, including calcium carbonate concretions. It is a caliche subsoil equivalent to the Kankar of India. The soils of areas of greater rainfall, such as the hills of the Shan States, are red with concretions of iron and manganese oxides in the subsoils. Thus in this warm monsoonal area, ancient red soils deposited at low altitudes in the basin mark increased rainfall; yellow limey soils, decreased rainfall. De Terra also assumes that increased rainfall, "Pluvial" climate, is associated with glaciation in the mountains and decreased rainfall with interglacial intervals or "Interpluvial" climate. This assumption is supported by the association of loess with "Pluvial" or immediately "post-Pluvial" deposits. Also alluviation and the building-up of terrace deposits in the piedmont belts is synchronous with glaciation in the mountains, whereas

erosion is characteristic of interglacial intervals. This interpretation is contrary to the interpretation of Huntington but is supported by Dainelli's work in the Inner Himalaya and that of De Terra and Paterson in northwestern India, of Penck and Bruckner in the Alps, of Bryan and Ray in the Rockies, and many others.

The terrace chronology leads to the subdivision of the Pleistocene of southeastern Asia into seven episodes—four glacial and three interglacial—as compared to the threefold subdivision based on vertebrate fossils. The First Glacial, and in places part of the First Interglacial, is represented by deformed beds containing a Villafranchian fauna and so far without known artifacts of man. In Java, however, the equivalent Djetis beds yielded the Modjokerto skull, the earliest known man. Parenthetically, the review of the Pleistocene geology in Java is of absorbing interest in its portrayal of the interaction of volcanic and tectonic phenomena in the building of an almost complete Pleistocene sequence. The well-known *Pithecanthropus* of Java and the *Sinanthropus* of China are of Second Glacial age. Movius shows that the artifacts of this age in Burma are of like pattern to those of Java and China. They differ widely from the stone tools of Europe and represent an ancient cultural differentiation characteristic of southeastern Asia. Nevertheless, they are recognizable and divisible into typological complexes whose correlation affords a second and independent line of proof that the geological correlation of De Terra is correct.

No review could do full justice to this outstanding example of co-operation in the historical sciences of geology and archeology. In method of work, in excellence of argumentation, and in completeness of illustration (attributable to the generous policy of the American Philosophical Society), this memoir is an inspiration to students of the Pleistocene.

KIRK BRYAN

Map Interpretation with Military Application. By WILLIAM C. PUTNAM. New York: McGraw-Hill Book Co., 1943. Pp. 67; pls. 10; figs. 26. $1.15.

As stated by the author in the Preface, "This book is designed primarily for Army and Navy R.O.T.C. students. The course is given two afternoons a week for a period of eight weeks." Being thus written for a specific group of students who have only a limited time for the subject, the book falls into the unavoidable error of not being general or inclusive enough for the "average" group or person interested in the military application of maps.

There are four chapters: (i) "Contour Maps," (ii) "Aerial Photographs," (iii) "Geologic Interpretations," and (iv) "Erosive Processes." Chapters i and ii, although very clearly written, are exceedingly "thumbnail," each chapter comprising six pages. For an advanced student of the subject these twelve pages may serve as a good review of basic principles so that what follows may be more readily understandable. But they will by no means satisfy the needs of the beginner. A case in point is that no mention is made in chapter i of the use of the military grid system for location of points—a method of location most often used in actual military operations. Further, in chapter ii, no reference is made to oblique photographs, although they are quite often used in areas of slight relief.

Chapters iii and iv are somewhat more expanded and contain many excellent aerial photographs, which greatly enhance the written material. As specific land forms are described, an appropriate topographic map is either provided or specified for further study of each feature. The topographic sheets are well chosen, because in many cases the map is from the area depicted by the aerial view in the text.

Perusal of this book leads the reviewer to the feeling that the title is somewhat misleading. There are very few instances where the military application of the point in question is mentioned. The method of application is most often left to the reader's imagination. "Geologic Interpretation of Maps and Aerial Photographs" would seem a more appropriate title.

Students and teachers of map interpretation who have familiarized themselves with the contents of the War Department's *Basic Field Manual 21–25* (elementary map and aerial-photograph reading) will find in Putnam's book a definite extension of their knowledge. The aerial photographs contained in the text would, by themselves, cost many times the purchase price of the book. Of interest to teachers is the page of selected references and page of indexed topographic maps and charts, which could be used in a course of map interpretation.

HERBERT D. HADLEY

PUBLICATIONS RECEIVED

Barry Lake Area, Abitibi County and Abitibi Territory. By R. L. Milner. Bureau of Mines Geological Report No. 14. Quebec: R. Paradis, Printer, 1943.

Biology, Ecology, and Morphogenesis of a Pelagic Foraminifer. By Earl H. Myers. Stanford University Publications, Biological Sciences, Vol. IX, No. 1. Stanford University, 1943.

Boundary-Layer Problems in the Atmosphere and Ocean. By C.-G. Rossby *et al.* Annals of the New York Academy of Science, Vol. XLIV, Art. 1. New York, 1943.

Carbonizing Properties and Petrographic Composition of Thick Freeport-Bed Coal from Harmar Mine, Harmarville, Allegheny County, Pennsylvania, and the Effect of Blending This Coal with Pocahontas No. 3- and No. 4-Bed Coals. By J. D. Davis *et al.* U.S. Bureau of Mines Technical Paper 655. Washington, D.C.: Government Printing Office, 1943.

Chemical Characteristics of Illinois Crude Oils with a Discussion of Their Geologic Occurrence. By O. W. Rees, P. W. Henline, and A. H. Bell. Report of Investigations No. 88. Urbana: Illinois State Geological Survey, 1943.

Choctaw County Mineral Resources. By Franklin E. Vestal and Thomas E. McCutcheon. Mississippi Geological Survey Bulletin 52. University, Miss., 1943.

Clay County. By Harlan R. Bergquist, Thomas E. McCutcheon, and Virginia H. Kline. Mississippi Geological Survey Bulletin 53. University, Miss., 1943.

Coal Resources of the Douglas Group in East-Central Kansas. By Arthur L. Bowsher and John M. Jewett. Kansas Geological Survey Bulletin 46. Lawrence, Kan., 1943.

The Control of Reservoir Silting. By Carl B. Brown. Department of Agriculture Miscellaneous Publication No. 521. Washington, D.C.: Government Printing Office, 1943.

Deep Water Well at the Jayhawk Ordnance Works in Cherokee County, Kansas. By G. E. Abernathy. Kansas Geological Survey Bulletin 47. Lawrence, Kan., 1943.

Eleventh Biennial Report of the Division of Geology. By Harold E. Culver, Supervisor. Olympia: State of Washington Department of Conservation and Development, 1943.

Eocene Foraminifera from the Type Lodo Formation, Fresno County, California. By Lois T. Martin. Stanford University Publications, Geological Sciences, Vol. III, No. 3. Stanford University, 1943.

Eocene of Virginia. By Benjamin Gildersleeve. Virginia Geological Survey Bulletin 57. University, Va., 1942.

Estudo comparativo entre as resistências à compressão de corpos de prova cilíndricos de concreto moldados e extraídos. By Jayme Ferreira da Silva, Jr., and André Aprá Netto. São Paulo, Brasil: Instituto de Pesquisas Tecnológicas de São Paulo, 1942.

Flavrian Lake Area: Beauchastel and Duprat Townships, Temiscamingue and Abitibi Counties. By W. G. Robinson. Division of Mineral Deposits, Geological Report 13, Department of Mines. Quebec: R. Paradis, Printer, 1943.

Flow of Heat from an Intrusive Body into Country Rock. By C. E. Van Orstrand. American Institute of Mining and Metallurgical Engineers Technical Bulletin No. 1677. Washington, D.C., 1944.

The Geology of the Cardigan and Rumney Quadrangles, New Hampshire. By Katharine Fowler-Billings and Lincoln R. Page. Concord, N.H.: New Hampshire State Planning and Development Commission, 1942.

Geology and Ground-Water Resources of Hamilton and Kearny Counties, Kansas. By Thad G. McLaughlin. Kansas Geological Survey Bulletin 49. Lawrence, Kan., 1943.

Geology and Mineral Resources of the Marseilles, Ottawa, and Streator Quadrangles. By H. B. Willman and J. Norman Payne. Illinois State Geological Survey Bulletin 66. Urbana, 1943.

A Geology of South Dakota, Part I: The Surface. By E. P. Rothrock. South Dakota State Geological Survey Bulletin 13. Vermillion, S.D., 1943.

The Geology of the Turtle River State Park. By Wilson M. Laird. North Dakota Geological

Survey Bulletin 16. Grand Forks, N.D., 1944.

Geophysical Investigations in the Tri-State Zinc and Lead Mining District. By J. J. Jakosky, R. M. Dreyer, and C. H. Wilson. Kansas Geological Survey Bulletin 44 and Engineering Experiment Station Bulletin 24. Lawrence, Kan., 1942.

Ground Water in the Oil-Field Areas of Ellis and Russell Counties, Kansas. By John C. Frye and James J. Brazil. Kansas Geological Survey Bulletin 50. Lawrence, Kan., 1943.

Illinois Mineral Industry in 1941. By Walter H. Voskuil, Douglas F. Stevens, and G. N. Oliver. Report of Investigations No. 87. Urbana: Illinois State Geological Survey, 1943.

Kansas Oil Field Brines and Their Magnesium Content. By Walter H. Schoewe with Chemical Analyses by R. Q. Brewster and Calvin Vander Werf. Kansas Geological Survey Bulletin 47, Part 2. Lawrence, Kan., 1943.

Kitchigama Lake Area, Abitibi Territory. By W. W. Longley. Division of Geological Surveys Geological Report 12, Department of Mines. Quebec: R. Paradis, Printer, 1943.

Laboratory Investigations on Bed-Load Transportation and Bed Roughness. By J. W. Johnson. Washington, D.C.: Sedimentation Section, Soil Conservation Service, U.S. Department of Agriculture, 1943.

Manganese-bearing Veins in Southwestern Virginia. By Anna I. Jonas. Virginia Geological Survey Reprint Series No. 5. University, Va., 1942.

The Manganese Deposits of the Turtle Mountains, North Dakota. By Thomas A. Hendricks and Wilson M. Laird. North Dakota Geological Survey Bulletin 15. Grand Forks, N.D., 1943.

Mica-bearing Pegmatites of Georgia. By A. S. Furcron and Kefton H. Teague. Geological Survey Bulletin No. 48. Atlanta, 1943.

The Mining Industry of the Province of Quebec in 1941. Quebec: R. Paradis, Printer, 1942.

Montgomery County Mineral Resources. Geology by Richard R. Priddy; Tests by Thomas E. McCutcheon. Mississippi State Geological Survey Bulletin 51. University, Miss., 1943.

New Methods in Stellar Dynamics. By S. Chandrasekhar. Annals of the New York Academy of Sciences, Vol. XLV, Art. 3. New York, 1943.

New Mollusks from the Round Mountain Silt (Tremblor) Miocene of California. By A. Myra Keen. Transactions of the San Diego Society of Natural History, Vol. X, No. 2. San Diego, Calif., 1943.

Notes on Reservoir Silting and Suspended-Load Measurements in Idaho. By L. C. Gottschalk. Sedimentation Section Special Report No. 4, Soil Conservation Service, U.S. Department of Agriculture. Washington, 1943.

Oregon Metal Mines Handbook. By the staff, Department of Geology and Mineral Industries, State of Oregon. Bulletin No. 14-C, Vol. II, Sec. 2. Jackson Co., 1943.

Pennsylvania Fusulinidae of Illinois. By Carl O. Dunbar and Lloyd G. Henbest. Illinois State Geological Survey Bulletin 67. Urbana, 1942.

Pontotoc County Mineral Resources. Geology by Richard R. Priddy. Tests by Thomas E. McCutcheon. Mississippi State Geological Survey Bulletin 54. University, Miss., 1943.

Reef Prospecting by the Resistivity Method in Uganda. By H. J. R. Way. American Institute of Mining and Metallurgical Engineers Technical Publication No. 1676. Washington, D.C., 1944.

The Relation between Centriole and Centromere in Atypical Spermatogenesis of Viviparid Snails. By Arthur W. Pollister and Priscilla F. Pollister. Annals of the New York Academy of Sciences, Vol. XLV, Art. 1. New York, 1943.

Report of the Committee on Marine Ecology as Related to Paleontology, 1941–1942. By Harry S. Ladd, Chairman. Washington, D.C.: National Research Council, 1942.

Report on the Reconnaissance Sedimentation Surveys of Loch Raven and Prettyboy Reservoirs, Baltimore, Maryland. By L. C. Gottschalk. Sedimentation Section Special Report No. 5, Soil Conservation Service, U.S. Department of Agriculture. Washington, D.C., 1943.

Report on the Sedimentation Surveys of Little Rock Reservoir, Los Angeles, California. By Carl B. Brown. Sedimentation Section Special Report No. 6, Soil Conservation Service, U.S. Department of Agriculture. Washington, D.C., 1943.

Report of the State Geologist on the Mineral Industries and Geology of Vermont, 1941–1942. By Albridge C. Jacobs. Montpelier, 1942.

Science and the War. By Various Authors.

Reprinted from the Transactions of the Kansas Academy of Science, Vol. XLVI. Lawrence, Kan., 1943.

Sillimanite, Kyanite, and Clay Deposits near Williamstown, South Australia. By A. R. Alderman. Transactions of the Royal Society of South Australia, Vol. LXVI (1942).

Sinop Vilâyeti, Boyabet Havzasi Petrol Sahasinin Jeolojik Tertibi, Seri A: Bildiriğler, No. 6. By Maurice M. Blumenthal. Türkiye Kretase Faunasi Etüdü Hakkinda, Seri B: Irdeller, No. 7. By V. Stchepinsky. Anadoluda bir kaç Lias Yatağinin Paleontolojik Tetkiki. Seri B: Irdeller. By Galib Otkun. Erzincan Mintakasinin Jeolojisi ve Maden Zenginlik leri. Seri C: Monografiler No. 2. By V. Stchepinsky. Publications de l'Institut d'Etudes et de Recherches Minières de Turquie. Ankara, 1942.

Some Mineral Deposits in the Area Surrounding the Junction of the Snake and Imnaha Rivers in Oregon. By F. W. Libbey. G.M.I. Short Paper No. 11. Portland, Ore.: Department of Geology and Mineral Industries, 1943.

Special Report on the Area from Forgues Lake to Johan Beet and North Shore of the St. Lawrence. By Jacques Claveau. Department of Mines, Division of Geological Surveys, P.R. No. 180. Quebec, 1943. (Mimeographed.)

Studies on Fresh-Water Bryozoa. XIV. The Occurrence of Stolella Indica in North America. By Mary Rogick. Annals of the New York Academy of Sciences. Vol. XLV, Art. 4. New York, 1943.

Subsurface Structure of the Base of the Kinderhook–New Albany Shale in Central and Southern Illinois. By Alfred H. Bell. Report of Investigations No. 92. Urbana: Illinois State Geological Survey, 1943.

Subsurface Structure and Oil Possibilities of Parts of Edwards, Richland, and Wabash Counties, Illinois. By William H. Easton. Press Bulletin Series No. 46. Urbana: Illinois State Geological Survey, 1943.

Water Flooding of Oil Sands in Illinois. By Frederick Squires and Alfred H. Bell. Report of Investigations No. 89. Urbana: Illinois State Geological Survey, 1943.

Wildcat Drilling in Illinois since 1936 with Discussion of Prospects for Further Discoveries and Table of Wildcat Wells Completed in 1942. By Charles W. Carter. Urbana: Illinois State Geological Survey, 1943.

MAPS RECEIVED

Maps of 20 complete quadrangles and portions of 4 other quadrangles covering the Chicago region to accompany Part I: Geology of the Chicago Region: General. By J Harlen Bretz. Illinois State Geological Survey Bulletin 65. Urbana, 1939.